U.S. Army Corps of Engineers
Earthquake Preparedness Center of Expertise
Urban Search & Rescue Training

BLOCK TITLE:	Structural Collapse Patterns
COURSE:	US&R Structures Specialist Training
BLOCK SCOPE/ OBJECTIVE:	At the end of this block, students will: Understand the principles of the ATC-21 Manual. Identify and describe problematical building types. Describe basic collapse patterns. Identify and describe earthquake collapse patterns. Describe collapse patterns caused by wind and flood.
TIME:	120 Minutes
PREREQUISITES:	Read Text Material Prior to Class
EVALUATION:	None
PERFORMANCE STANDARDS:	Full Class Attendance Completion of Practical Exercise
PREPARED BY:	Mr. David Hammond, Structural Engineer
EDITION:	3
DATE:	June 1, 1993
APPROVED BY:	EQPCE Curriculm Review Panel

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Earthquake Preparedness Center of Expertise
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STRUCTURAL COLLAPSE PATTERNS

Student Notes

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STRUCTURAL COLLAPSE PATTERNS

Student Notes cont.

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STRUCTURAL COLLAPSE PATTERNS

Student Notes cont.

1.3 STRUCTURAL COLLAPSE PATTERNS

OVERVIEW

1. **In this section we will discuss the following:**

   a) **The ATC-21 method of Building Classification**
   b) **Basic Loading and Common Failure Patterns**
   c) **Earthquake Caused Collapse Patterns**
   d) **Wind and Flood Caused Collapse Patterns**

ATC-21 NOMENCLATURE

1. ATC-21, Rapid Visual Screening of Buildings For Potential Seismic Hazards funded by FEMA and written by Applied Technology Council in 1988.

2. Method is intended to be used in sidewalk survey of existing buildings to preliminarily determine location of buildings susceptible to earthquake damage. It's expected to take less than 30 minutes per building to obtain data and complete the form.

3. Buildings would be rated from 6.5 good to less than 2 which would be potentially hazardous, requiring further study (see BF-1).

4. There are twelve building types listed (see BF-2), and these are discussed in detail in the ATC-21 document pages 14 through 37.

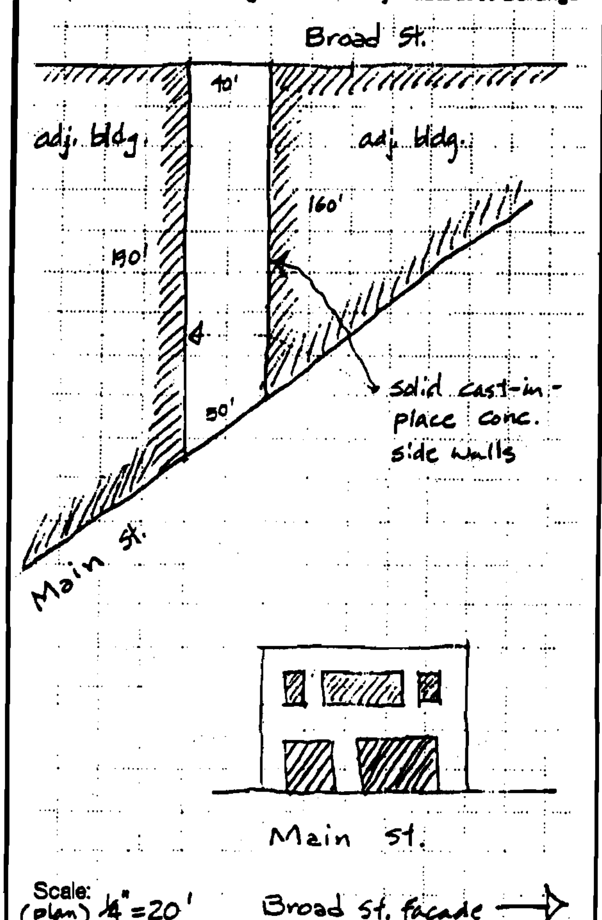
5. Figures BF-3 through 14 illustrate each type of building and show the different variations possible for floor and wall materials.

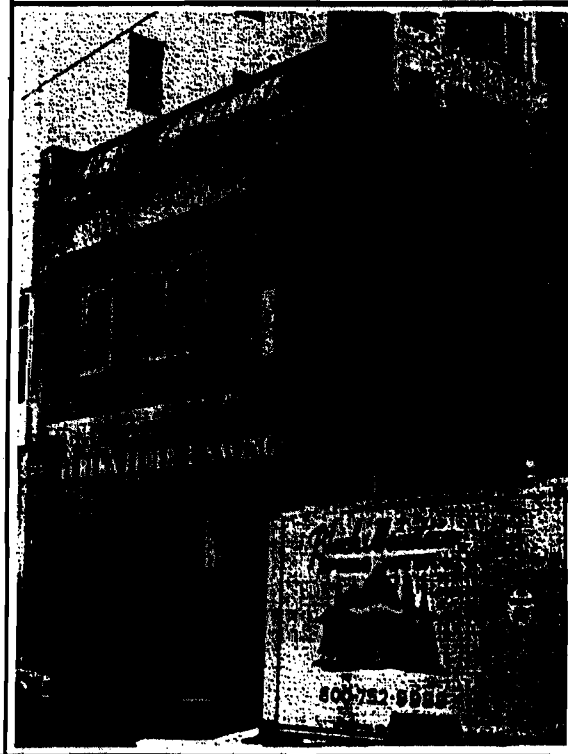
6. S2, C1, C2, C3/S5, TU, PC2 and URM are expected to be most susceptible to earthquake damage. Wood residential structures have also provided a large number of failures in California, since they are, by far the most prevalent type. However, due to their relatively light weight and small size, people are seldom entrapped in wood residences. Type S3 is listed since it is very susceptible to damage by wind. Many S1 (Steel Frames) structures experienced cracks in their welded connections during the Northridge (L.A.) quake, which is of great concern to the engineering design profession. However, since none of these buildings were damaged to an extent that would cause even partial collapse, they are not currently considered probable for Urban Search & Rescue operations.

ATC-21/ (NEHRP Map Areas 5,6,7 High)	
Rapid Visual Screening of Seismically Hazardous Buildings	

Address 570 - 574 Main
Anytown Zip 12345
Other Identifiers
No. Stories 2 Year Built 1922
Inspector KW Date 3/11/88
Total Floor Area (sq. ft) 16,190
Building Name
Use bank, office

(Peel-off label)





OCCUPANCY	No. Persons
Residential	0–10
Commercial	11–100
Office	100+
Industrial	
Pub. Assem.	
School	
Govt. Bldg.	
Emer. Serv.	
Historic Bldg.	

Non Structural Falling Hazard ☐

DATA CONFIDENCE

* = Estimated, Subjective, or Unreliable Data

DNK = Do Not Know

STRUCTURAL SCORES AND MODIFIERS

BUILDING TYPE	W	S1 (MRF)	S2 (BR)	S3 (LM)	S4 (RC SW)	C1 (MRF)	C2 (SW)	C3/S5 (URM INF)	PC1 (TU)	PC2	RM	URM
Basic Score	4.5	4.5	3.0	5.5	3.5	2.0	3.0	1.5	2.0	1.5	3.0	1.0
High Rise	N/A	-2.0	-1.0	N/A	-1.0	-1.0	-1.0	-0.5	N/A	-0.5	-1.0	-0.5
Poor Condition	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Vert. Irregularity	-0.5	-0.5	-0.5	-0.5	-0.5	-1.0	-0.5	-0.5	-1.0	-1.0	-0.5	-0.5
Soft Story	-1.0	-2.5	-2.0	-1.0	-2.0	-2.0	-2.0	-1.0	-1.0	-2.0	-2.0	-1.0
Torsion	-1.0	-2.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
Plan Irregularity	-1.0	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-1.0	-1.0	-1.0	-1.0
Pounding	N/A	-0.5	-0.5	N/A	-0.5	-0.5	N/A	N/A	N/A	-0.5	N/A	N/A
Large Heavy Cladding	N/A	-2.0	N/A	N/A	N/A	-1.0	N/A	N/A	N/A	-1.0	N/A	N/A
Short Columns	N/A	N/A	N/A	N/A	N/A	-1.0	-1.0	-1.0	N/A	-1.0	N/A	N/A
Post Benchmark Year	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	+2.0	N/A	+2.0	+2.0	+2.0	N/A
SL2	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3
SL3	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6	-0.6
SL3 & 8 to 20 stories	N/A	-0.8	-0.8	N/A	-0.8	-0.8	-0.8	-0.8	N/A	-0.8	-0.8	-0.8
FINAL SCORE						1.4						

COMMENTS
- renovated facade and interior, side walls still show original cast-in-place concrete
- assume frame action in transverse direction

Detailed Evaluation Required? YES NO

Figure BF-1

STRUCTURAL BUILDING TYPES - ATC-21-1

I.D.	GENERAL DESCRIPTION
W	WOOD BUILDING OF ALL TYPES
S1	STEEL MOMENT RESTING FRAMES
S2	BRACED STEEL FRAMES
S3	LIGHT METAL BUILDINGS
S4	STEEL FRAMES W/CAST IN PLASCE CONC WALLS
C1	CONCRETE MOMENT RESISTING FRAMES
C2	CONCRETE SHEAR WALL BUILDINGS
C3/S5	CONCRETE/STEEL FRAME W/URM INFILL WALLS
TU	TILT-UP CONCRETE WALL BUILDINGS
PC2	PRECAST CONCRETE FRAME BUILDINGS
RM	REINFORCED MASONRY BUILDINGS
URM	UNREINFORCED MASONRY BUILDINGS

PROBLEM BUILDINGS

W	1 TO 3 STORY HOUSES & 2 TO 4 STORY APARTMENTS (ESPECIALLY PRE 1940)
URM	1 TO 8 STORY (MOST LESS THAN 3 STORY) ALSO STEEL & CONCRETE FRAMES W/URM INFILL
C1/C3	PRE 1971 BLDGS (ESPECIALLY PRE 1940)
PC2/TU	FACTORY BUILT PRECAST & TILT UP WALL (OLDER POORLY CONNECTED BLDGS)
S2	BRACED STEEL FRAMES (COLUMN CAPACITY LESS THAN BRACE CAPACITY)
OTHERS	BUILDINGS WITH IRREGLARITIES SOFT FIRST AND OTHER STORY BLDGS OPEN FRONT AND CORNER BUILDINGS

Figure BF-2

PROBLEMATICAL BUILDING TYPES

1. **Wood Frame Building- W** (see BF-3, BF-4) These structures can vary from 1 to 4 stories and contain from one to tens of living units. The principle weakness may be in lateral strength of walls, or interconnection of structure, especially at the foundation. Common problems in strong earthquakes are:

   a) Walls that are weakened by too many openings become racked (rectangles become parallelograms). This can cause a significant offset of one floor from another and in severe cases collapse has occurred.

   b) Relatively modern 2 and 3 story wood apartment buildings may have walls that are braced using only plaster/gypsum board, let-in bracing, or inadequately designed plywood. These structures may experience brittle, first story failures, especially when upper story walls do not align with those in the lower story.

   c) Wood houses with crawl spaces can shift or slide off their foundations.

   d) Masonry chimneys can crack and fall off or into the structure.

   e) Masonry veneers can fall off walls and shower adjacent areas with potentially lethal objects.

   f) Structures can separate at offsets in floor/roof levels (such as porches and split level houses).

   g) There is a great danger of fire in these structures due to the presence of so much fuel.

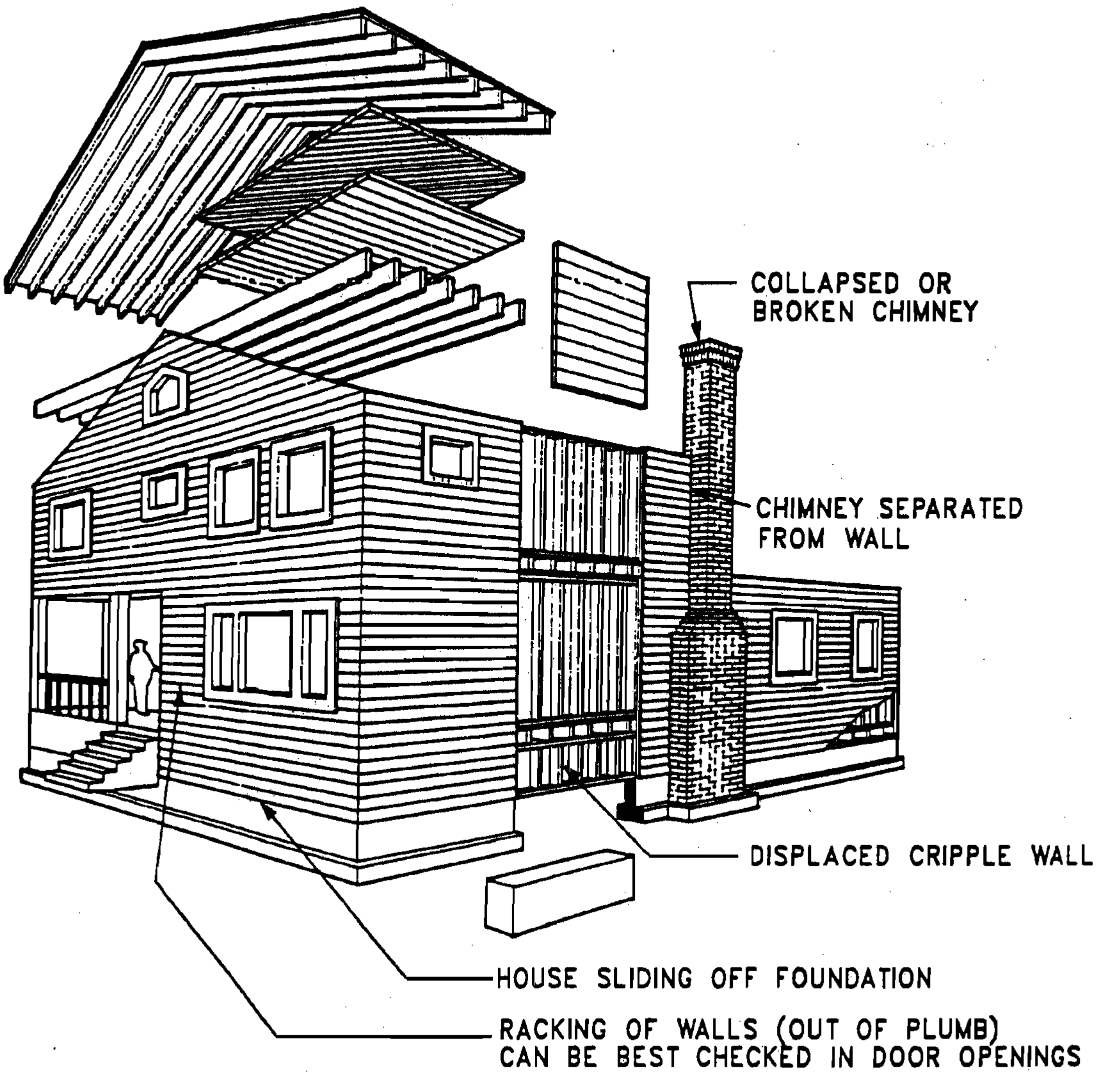
2. **Diagonally Braced Steel Frames- S2** (see BF-5, BF-6) may be from one to twenty story office buildings with glass or other non-structural exterior covering. Steel buildings in general have performed well, but those with diagonal bracing have had the following problems:

   a) Buildings that contain slender rod cross bracing may have excessive distortion (story drift) which can lead to shedding or significant damage to brittle, finish materials such as glass, masonry veneer, or precast concrete panels.

   b) Whipping action has caused some slender cross braces to break.

   c) When the braces/columns are not properly proportioned, especially in taller frames, the great tension strength of the braces can cause compression (buckling) failure of columns. This effect is attributed to the catastrophic failure of the Pino Suarez, 20 story tower in Mexico City 1985.

OLDER WOOD HOUSES



OTHER HAZARDS

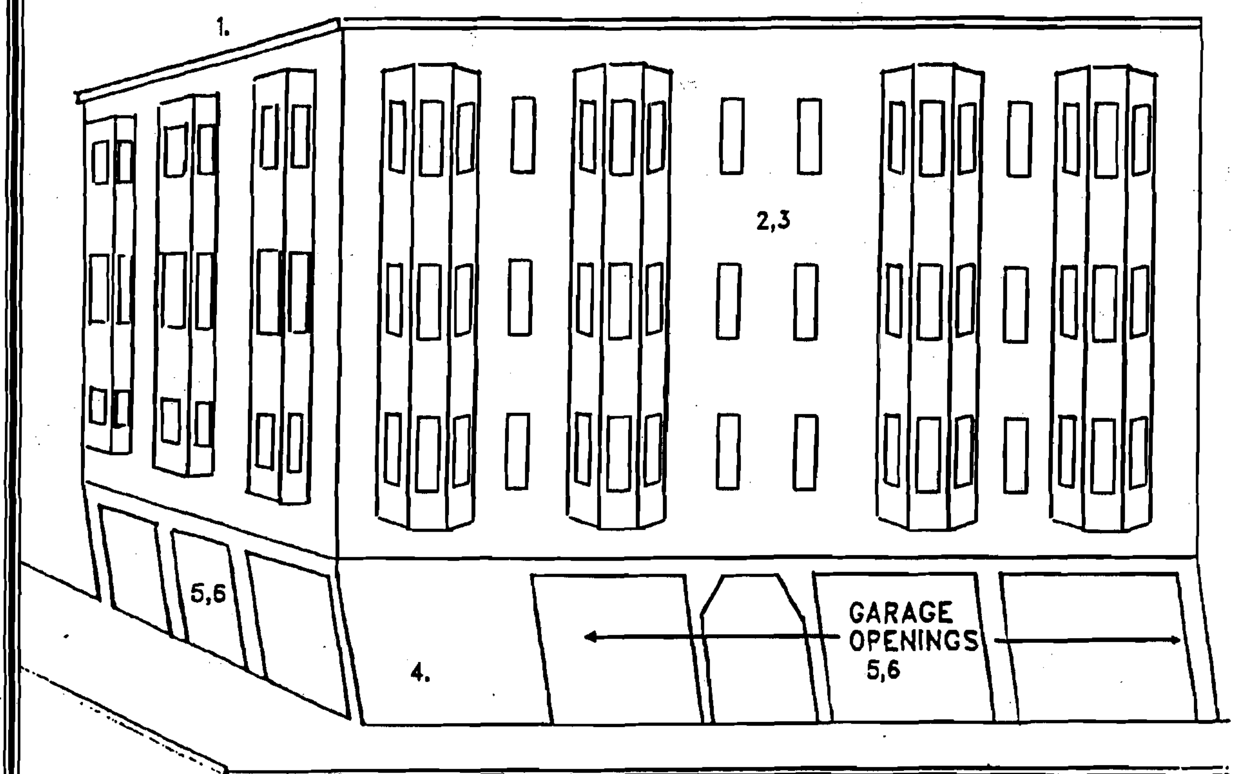
- AFTERSHOCKS CAN CAUSE DANGEROUS CONDITIONS TO BECOME WORSE (A CRACKED CHIMNEY CAN BECOME A LETHAL FALLING OBJECT)
- CHECK GAS, ELECTRIC, & WATER METERS FOR SPINNING DIALS THAT INDICATE BROKEN PIPES AND/OR ELECTRICAL SHORTS
- CHECK WATER HEATER, RANGE, & FURNACE FOR BROKEN PIPES
- CHECK KITCHEN, GARAGE, & LAUNDRY FOR SPILLED CHEMICAL HAZARDS

Figure BF-3

WOOD APARTMENT BUILDINGS

1. ROOF AND FLOORS HAVE 2x WOOD JOIST SPACED AT 16" O.C. AND ARE SHEATHED WITH 1x WOOD UNLESS BUILT AFTER 1945 (PLYWOOD SHEATHING USED AFTER 1945)
2. WALLS MAY BE COVERED WITH PLASTER OR OTHER FINISH OVER 2x4 WOOD STUDS SPACED AT 16" O.C.
3. WALLS OF BUILDINGS BUILT PRIOR TO 1935 ARE NORMALLY SHEATHED WITH HORIZONTAL 1x SHEATHING. THIS HAS ONLY MINIMAL RESISTANCE TO WIND & EARTHQUAKE SHEAR FORCES

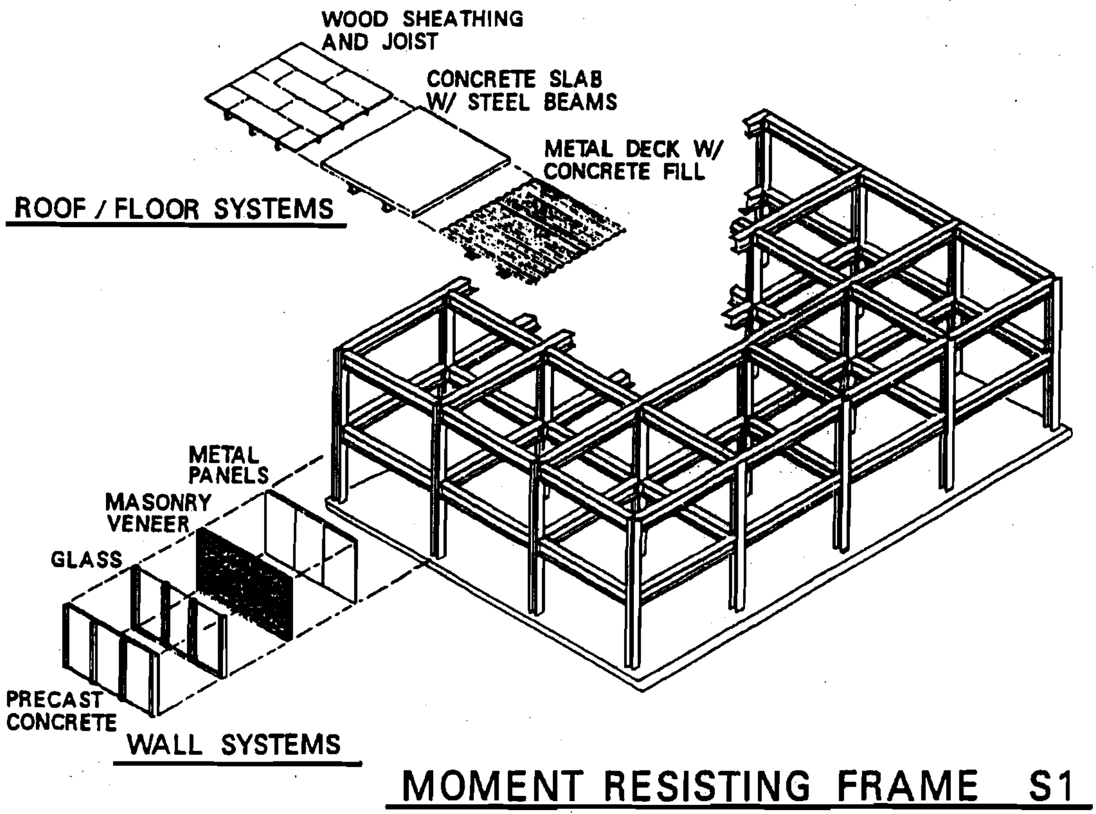
   DIAGONAL 1x SHEATHING WAS OFTEN USED IN CALIFORNIA AFTER 1934. PLYWOOD SHEATHING STARTED TO BE USED IN SOME BUILDINGS IN 1945 AND WAS USED IN MOST AFTER 1955. BOTH TYPES GIVE FRAME CONSTRUCTION GREATER EARTHQUAKE RESISTANCE THAN HORIZONTAL OR VERTICAL SHEATHING.



4. WALLS MAY HAVE MASONRY VENEER, ESPECIALLY LOWER STORY
5. THE FIRST STORY GARAGE OPENINGS CREATE THE CONDITION FOR A SOFT STORY. THIS CAN BE OVERCOME BY USING PROPERLY DESIGNED WOOD WALLS OR BY CONSTRUCTING A SHEARWALL BRACED, ONE STORY CONCRETE, GARAGE STRUCTURE.
6. UNFORTUNATELY THERE ARE MANY 2 AND 3 STORY, MODERN BUILDINGS OF THIS TYPE THAT HAVE ONLY PLASTER OR INADEQUATE PLYWOOD WALLS IN THE FIRST STORY. THEY ARE SUSCEPTIBLE TO SEVERE EARTHQUAKE DAMAGE AND/OR COLLAPSE

Figure BF-4

STEEL FRAME BUILDINGS S1 & S2



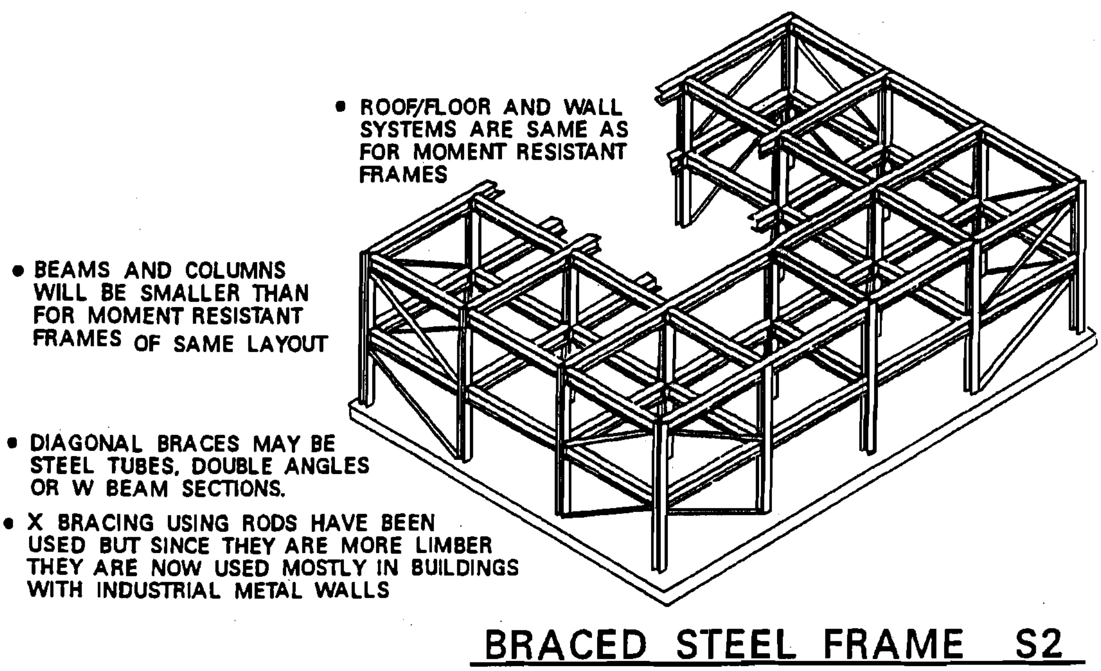
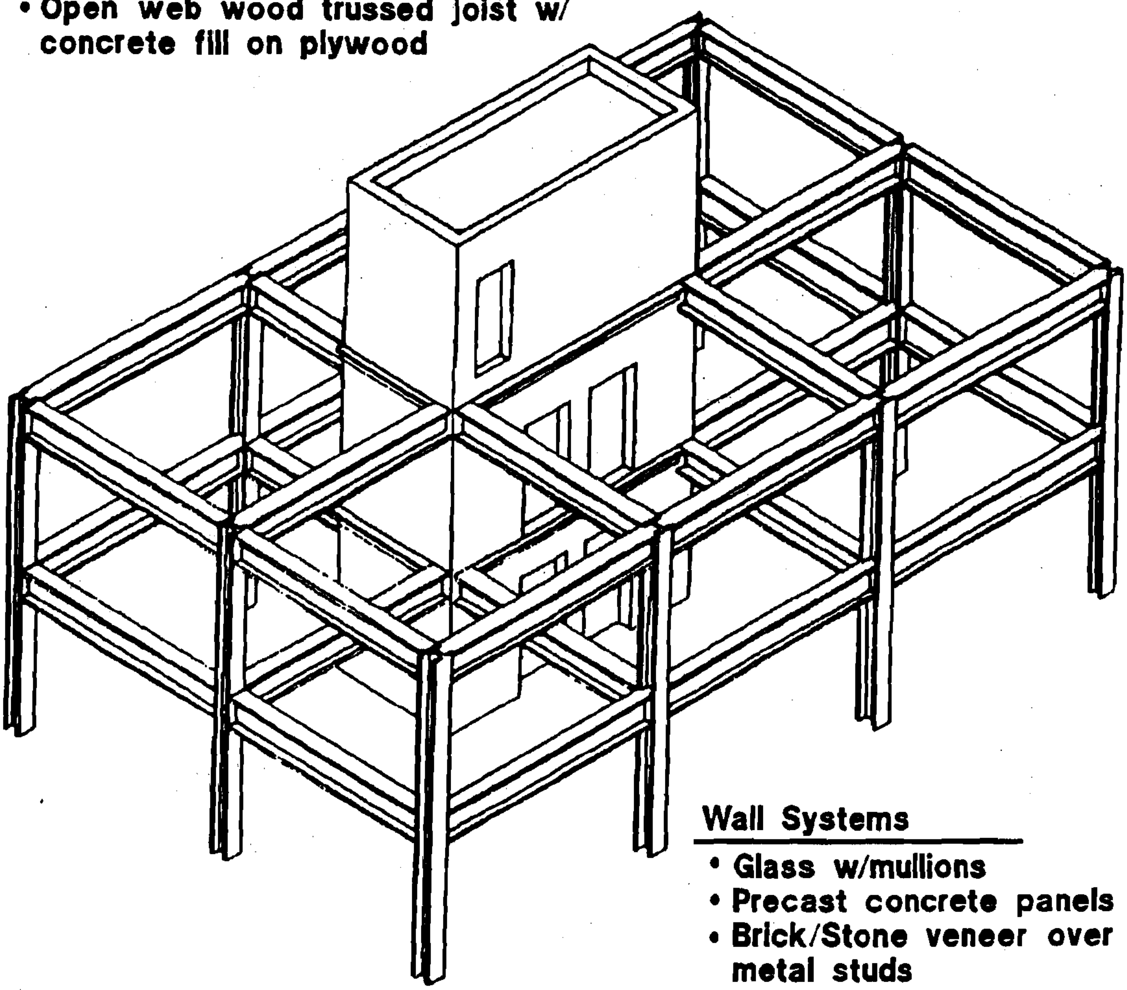


Figure BF-5

STEEL MOMENT RESISTING FRAME

Floor/Roof Systems

- Wood joist & sheathing
- Reinforced concrete w/steel beams
- Corrugated metal deck w/concrete fill & steel beams or open web joist
- Open web wood trussed joist w/ concrete fill on plywood



Wall Systems

- Glass w/mullions
- Precast concrete panels
- Brick/Stone veneer over metal studs
- Wood or plaster over wood or metal studs
- Unreinforced masonry infill

STEEL FRAME BUILDING S1 & S4

CONCRETE SHEARWALL AT S4 ONLY

Figure BF-6

d) When tube type members are used for diagonals, sudden premature local crippling of the members has resulted. This can occur when cold rolled tubes are used, since high stresses are originally induced during forming.

e) Inadequate detailing or workmanship at connections has caused local failures, such as buckling of connections plates and roll over of beams. Although collapse has not resulted from these failures, significant non-structural damage has occured.

3. **Light Metal Buildings- S3** (see BF-7) are normally one story pre-engineered buildings sheathed with metal siding and roofing. These structures have been damaged during earthquakes due to poor connections and field errors such as incomplete welding of joints but mostly they respond well due to their lack of mass and abundance of flexibility. During strong windstorms, however, Light Metal Structures have exhibited the following problems:

a) Building wall and roof loose roof sheathing, purlins and girts, that were braced by the sheathing will then buckle, often leading to progressive buckling collapse of entire structure.

b) Doors and windows are blown in leading to greatly increased outward pressures on leeward wall and roof followed with shedding of sheathing and in most severe cases progressive collapse (as in a. above).

c) Tie-rod bracing can be broken or stretched by whipping action. Also, rod end connections can fail by pullout, prying action, etc.

d) Lower chord bracing at end walls can buckle due to wind pressure on wall.

e) Since these structures have little redundancy, performance is usually governed by "WEAKEST LINK" behavior, (failure of one element can lead to progressive/domino type collapse).

LIGHT METAL BUILDINGS S3

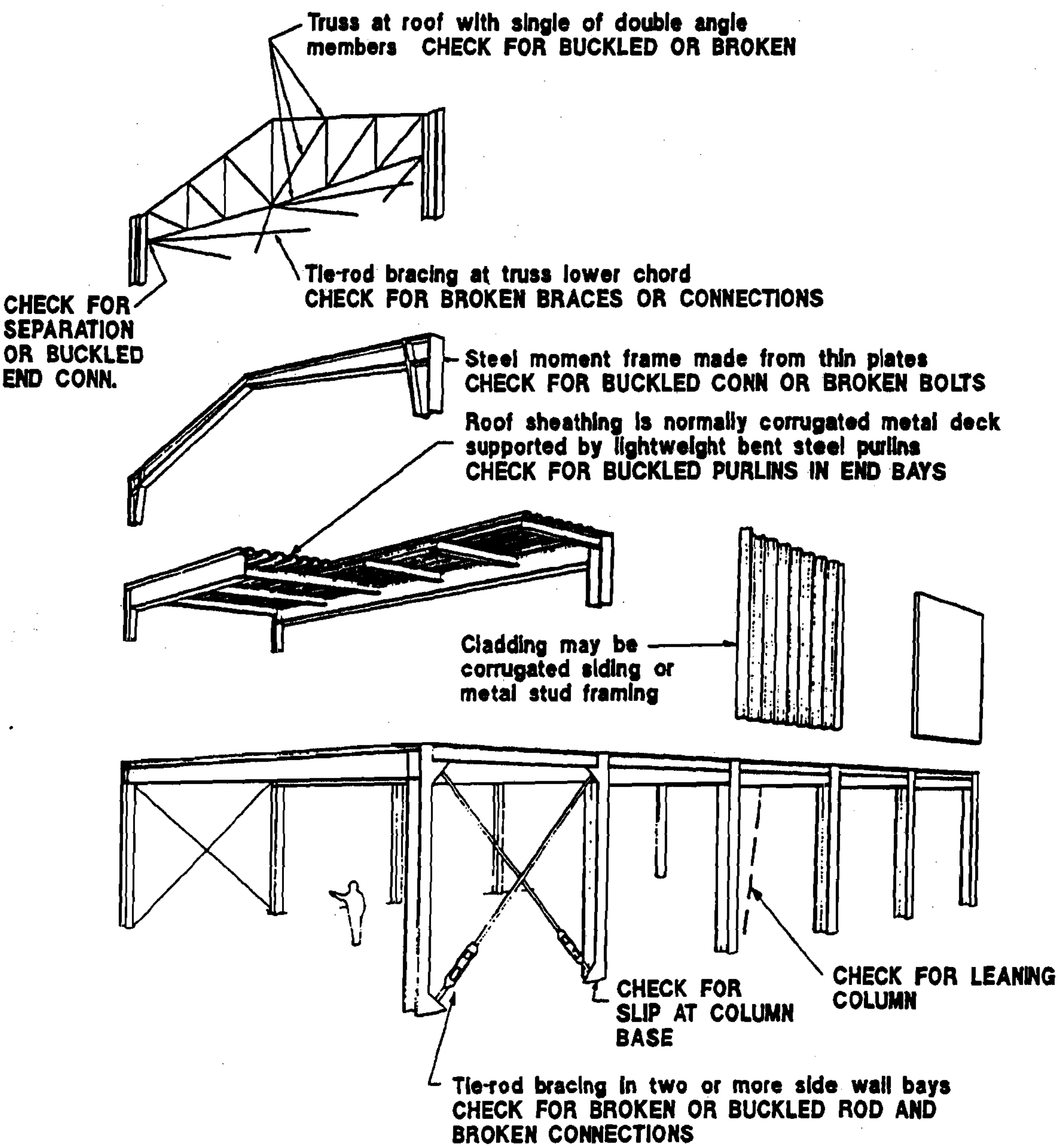


Figure BF-7

4. **Concrete Frame Buildings- C1, C3** (see BF-8, BF-9) usually are from one to thirteen stories high, and may have URM infill walls. Older frames in California had thin concrete infill walls on property lines in some cases. The most hazardous configurations include: soft (high, open) first stories; open front buildings (typical of retail, one and two story); and corner buildings (torsion problems). The common earthquake problems are:

   a) Columns break at intersections with floor beam. Inadequate rebar and ties don't confine the concrete when subjected to high shear and tension stresses. Failures may be driven by strong P-Delta effect.

   b) Short columns in exterior walls get high shear and tension stresses focused into them by surrounding massive concrete.

   c) Bending and punching shear failure at intersections of flat slabs (waffle, etc.) and columns.

   d) URM infill can fall off, often pop out of surrounding frames. Also, URM infill can cause columns to shear off at floor line or top of URM.

   e) Weak concrete and poor construction can make all above conditions worse and more likely to lead to larger collapse, which will be discussed later.

5. **Concrete Shearwall Building- C2** are from one to thirteen stories high with walls on all four sides and/or within the structure as corridor/stair or other divisions between spaces. Walls may have openings "punched-in" as doors or windows, but in more modern buildings, the openings may be in groups that are placed between solid wall sections. These buildings rarely collapse in earthquakes but damage can occur, such as:

   a) X-cracking of wall sections between punched-in openings.

   b) Severe cracking of shallow wall/floor header sections that frame between solid wall sections.

   c) Severe cracking or collapse of columns that occur in "soft stories" of otherwise uniformly stiff shearwall buildings (soft first story, etc.).

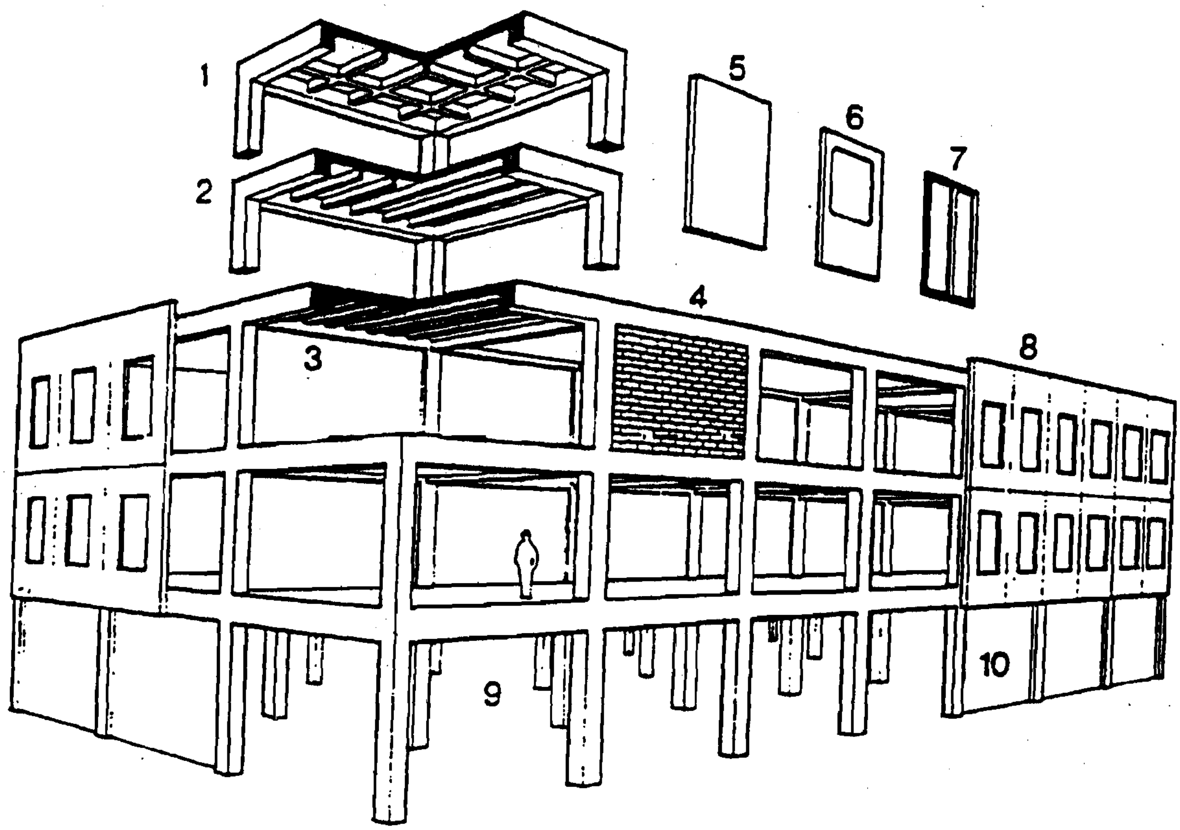
6. **Precast Concrete Frame- PC2** (see BF-10) usually one to ten stories tall, although precast wall panels may be used in taller buildings. Floors/roof may be tee, double tee, or hollow core concrete plank sections supported by precast girders and columns. Lateral resistance is often provided by reinforced masonry or concrete walls, but buildings that rely on moment frame resistance have performed very poorly (Armenia). The common earthquake failures are:

   a) Joint failures- joints between roof/floor and walls, between roof panels, between wall panels and joints between floor beams and columns. This can lead to complete collapse as the building breaks into very large parts.

CONCRETE MOMENT RESISTING FRAME C1

Roof/floor diaphragms:
1. concrete waffle slab
2. concrete joist and slab
3. steel decking with concrete topping

Curtain wall/ non-structural infill:
4. masonry infill walls
5. stone panels
6. metal skin panels
7. glass panels
8. precast concrete panels

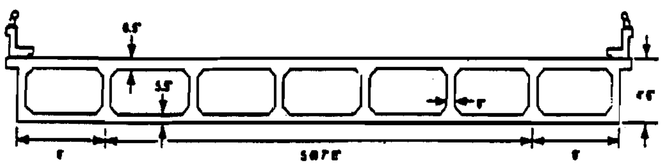


Structural system:
9. distributed concrete frame

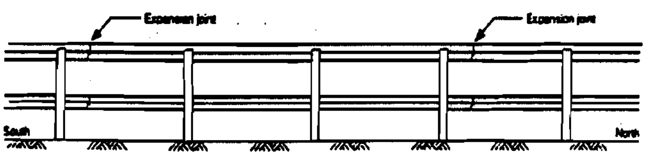
Details:
10. typical tall first floor (soft story)

Figure BF-8

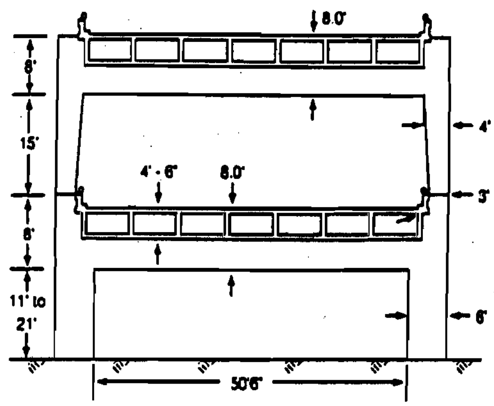
2 STORY HIGHWAY BRIDGE I-880



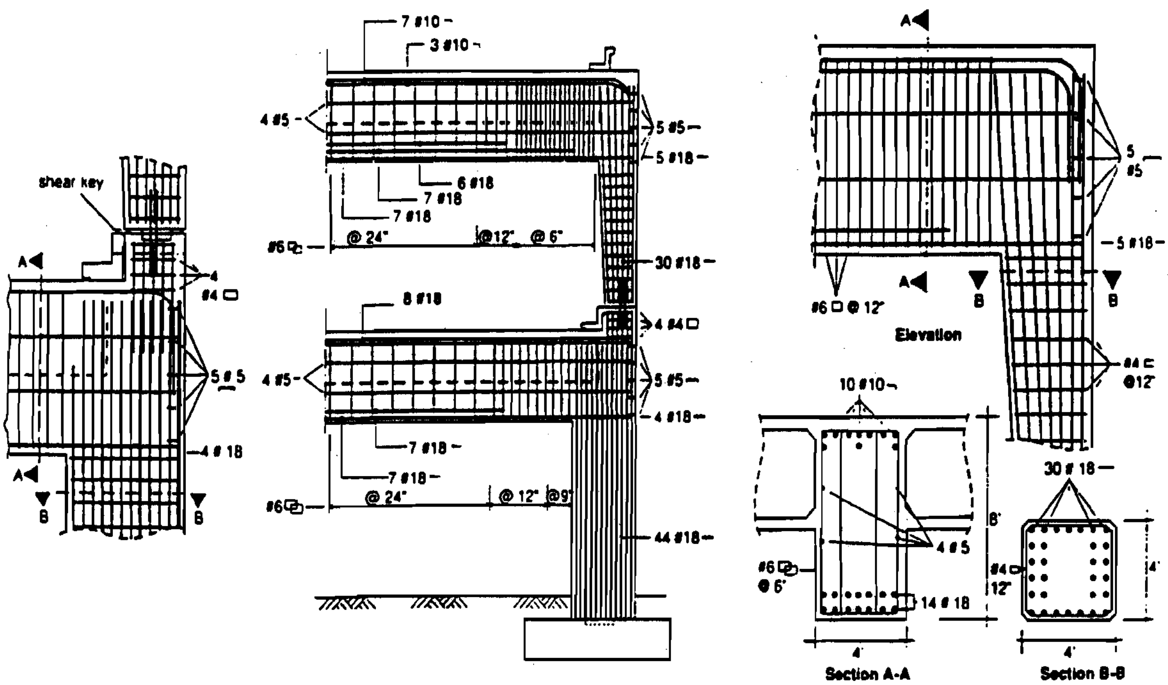
TYPICAL ROADWAY SECTION



TYPICAL SIDE ELEVATION/LAYOUT



TYPE B1 BENT



TYPE B1 BENT DETAILS AND DIMENSIONS

Figure BF-8a (Information Only)

CONCRETE SHEARWALL BLDG C2

Roof/floor span systems:
1. heavy timber rafter roof
2. concrete joist and slab
3. concrete flat slab

Wall system:
4. interior and exterior concrete bearing walls
5. large window penetrations of school and hospital buildings

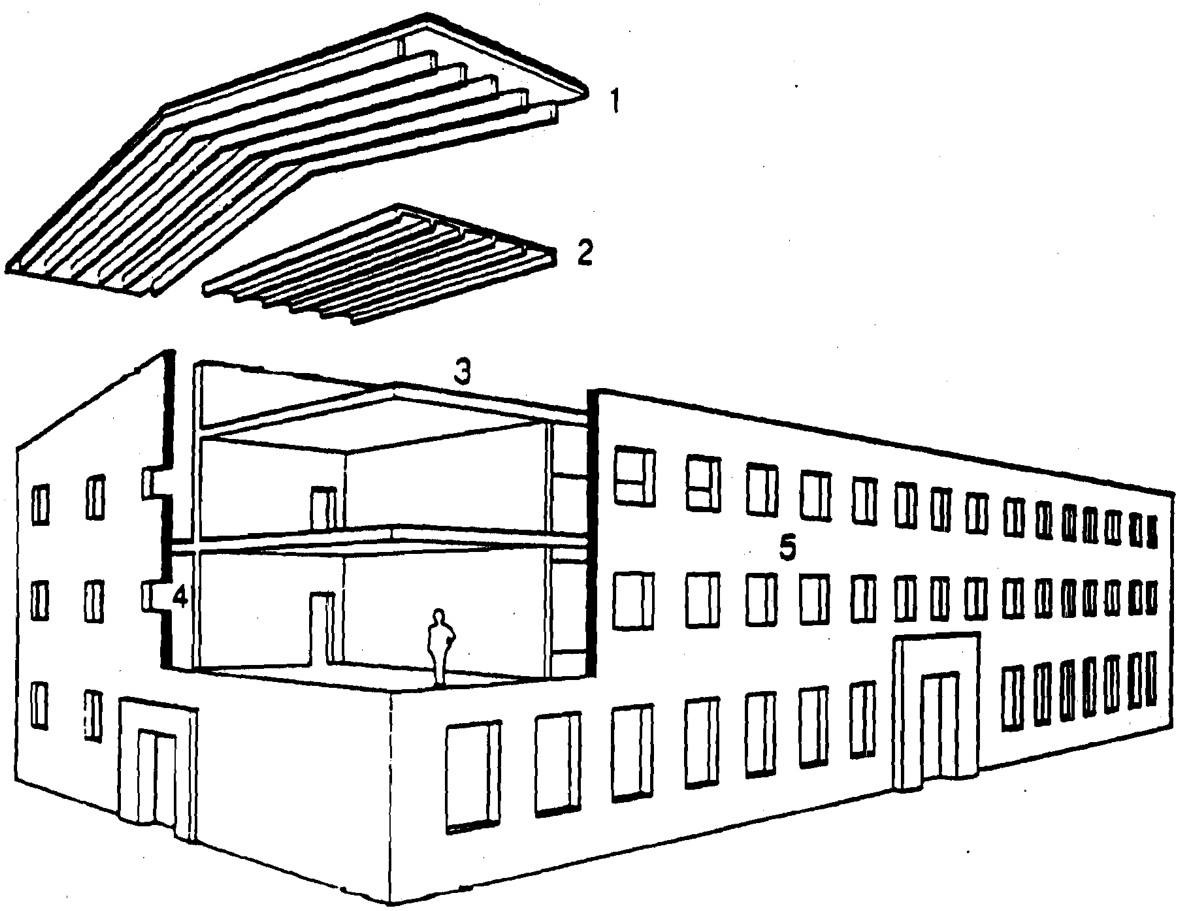
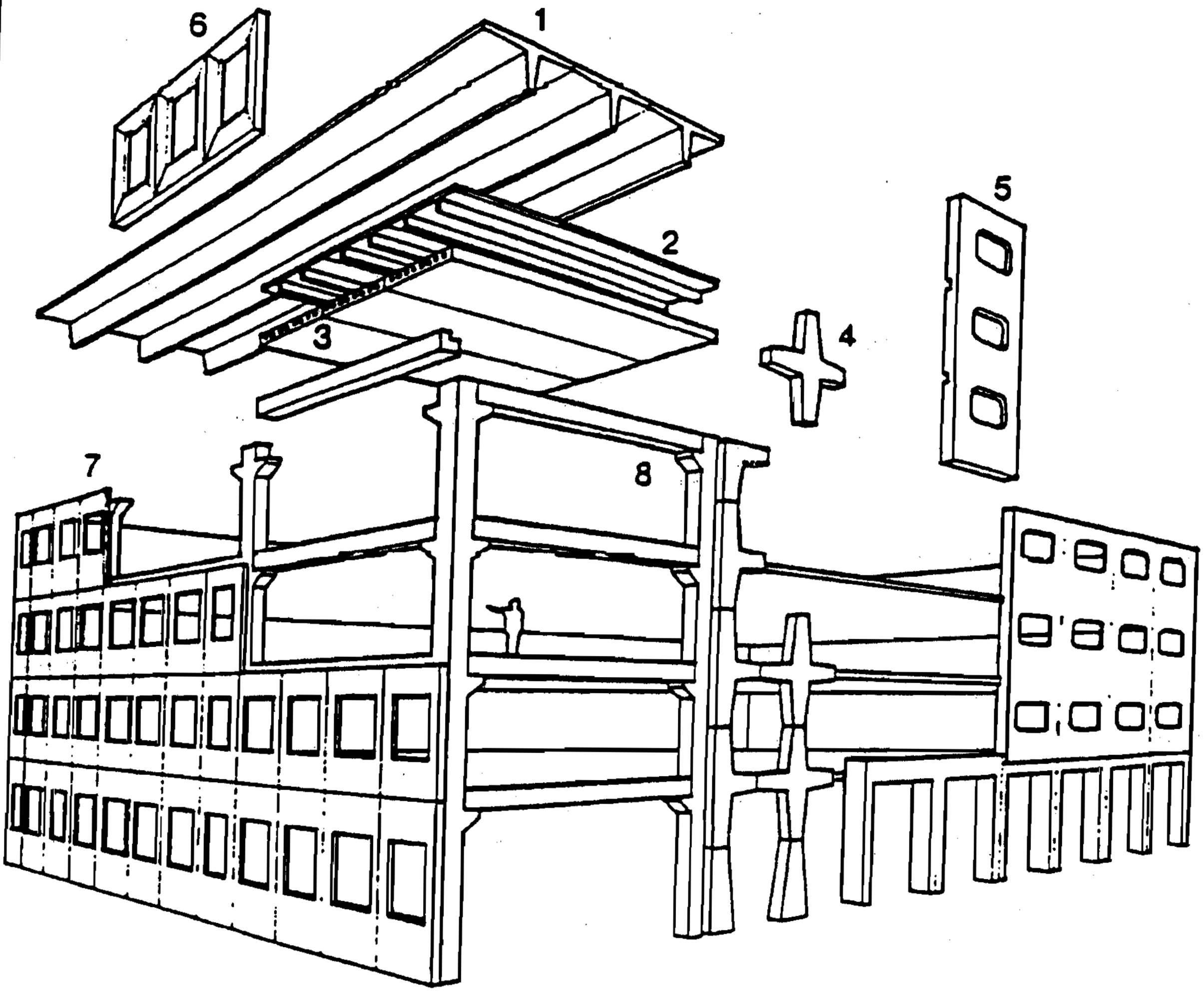


Figure BF-9

PRECAST CONCRETE BUILDINGS PC2

Roof/floor span systems:
1. structural concrete "T" sections
2. structural double "T" sections
3. hollow core concrete slab

Wall systems:
4. load-bearing frame components (cross)
5. multi-story load-bearing panels



Curtain wall system:
6. precast concrete panels
7. metal, glass, or stone panels

Structural system:
8. precast column and beams

PRECAST CONCRETE FRAME W/ SHEARWALLS

Figure BF-10

b) Wall panels separate from building and fall off. If panels are non bearing only local failure may be the result. In cases the floors/roof supported by the walls can also collapse.

c) Progressive collapse can be caused by a joint failure between column and beam or slab and wall panel. This then results in failure of the structure just above, due to lack of support, and also to the structure below, due to heavy debris loading (see BF-18).

6. **Post-tensioned Lift Slabs-** (see BF-11) are buildings from 3 to 13 stories high, made with thin (6 to 8") flat slabs poured as pancake stacks and then lifted into place on concrete or steel columns. They are laterally braced with cast in place concrete shear walls that form elevator or stair wells and/or reinforced masonry shear walls.

Not listed in ATC-21, but included here since spectacular collapses have occurred.

a) A six story apartment building of this type collapsed in the 1964 Alaska earthquake due to overturning of the stair cores. A twelve story building of this type collapsed during construction in 1987.

b) The resulting collapsed structures have very closely spaced broken slabs that are essentially unreinforced concrete. The unbounded reinforcing cables become loose during collapse, leaving the concrete essentially unreinforced. The lack of projecting beams, in this type of construction, can result in very close spacing of collapsed slabs.

7. **Tilt Up Concrete Wall Buildings- TU** (see BF-12) are usually one story buildings with wood roof, but may be up to three stories. May have wood floors, concrete floors, steel framing with concrete filled metal deck floors, or with up to 1 1/2" concrete or other fill on wood floor. The common earthquake problems are:

a) Walls separate from wood floors/roof causing at least local collapse of floor/roof, possible general collapse of walls and floor/roof.

<u>Note:</u> This problem occured during the Northridge Earthquake to approximately 400 buildings, most of which had strap connections that were cast into walls and bolted to roof members. More substantial connections, that can resist both tension and compression, appear to be required, since it has been demonstrated that forces as high as 200% G can be generated at the mid-span of wood roof diaphragms in this type of building.

b) Suspended wall panels fall off building.

<u>Note:</u> Suspended panels could be a problem on S1, S2, C1, C2, PC2, and RM buildings.

POST TENSIONED LIFT SLAB BUILDING

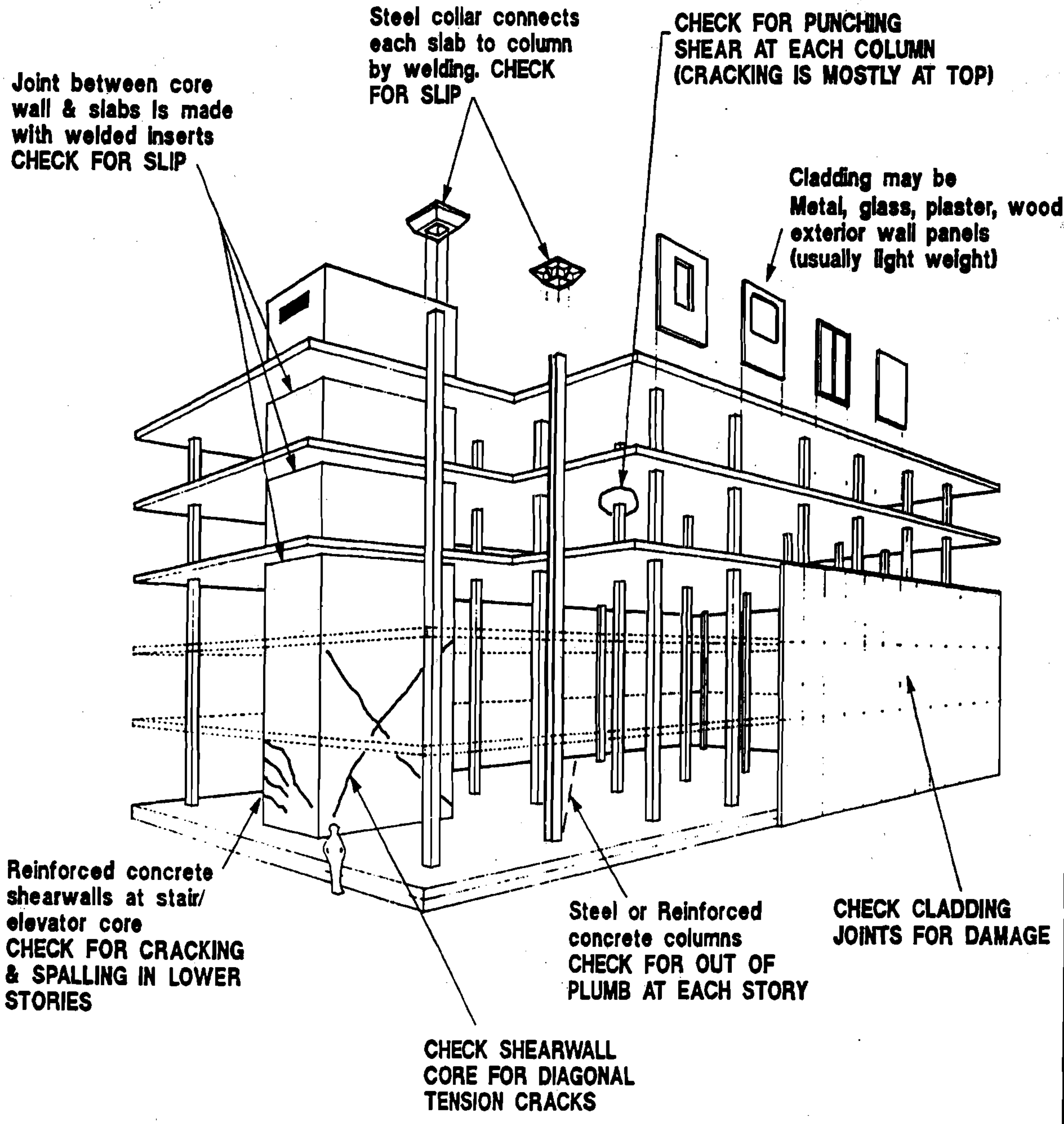
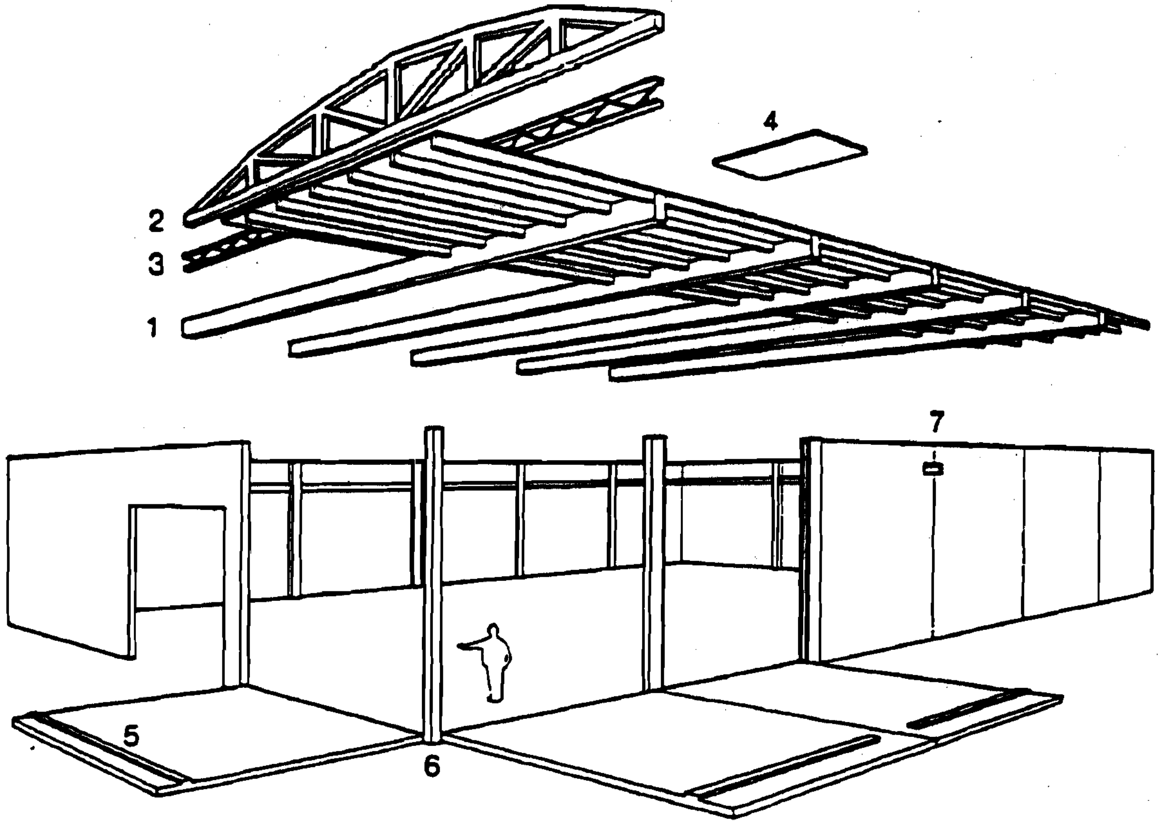


Figure BF-11

TILT-UP CONCRETE WALL BUILDING

Roof/floor span systems:
1. glued laminated beam and joist
2. wood truss
3. light steel -web joist

Roof/floor diaphragms:
4. plywood sheathing



Details:
5. anchor bolted wooden ledger for roof/floor support

Wall systems:
6. cast-in-place columns– square, "T" shape, and "H" shape
7. welded steel plate type panel connection

ONE STORY TILT-UP BUILDING (MAY ALSO BE 2 OR 3 STORY)

Figure BF-12

c) Walls may have short, weak columns between window openings that fail due to inadequate shear strength.

d) Large buildings that are Tee, or L, or other non rectangular shape in plan, can have failures at the intersecting corners. The major weight of these buildings is normally in the walls, and most failures are limited to exterior bays of the buildings, supported by the walls.

8. **Unreinforced Masonry Buildings- URM** Usually from 1 to 6 story buildings with URM bearing walls and wood floors (see BF-13, BF-14). There are estimated to be as many as 50,000 in California. This would include steel and concrete frames with URM infill (see BF-15). In addition to these, there are unreinforced or under-reinforced hollow concrete block walls, masonry veneer on wood or metal studs, and native stone, adobe, ect. bearing wall structures. Common earthquake problems are:

a) Parapets and full walls fall off buildings due to inadequate anchors.

b) Multi thickness walls split and collapse or break at openings. Mortar is often weak and made with too high a lime content.

c) Walls that are more heavily loaded by roof and floors tend to perform better than walls that are parallel to framing, since load of floor etc., tend to compress bricks together.

d) Roof/floors may collapse if there are no interior wall supports and if the earthquake has a long enough duration.

e) Cavities usually form by wood floors in familiar patterns of Vee, Lean-to, and complicated Pancake.

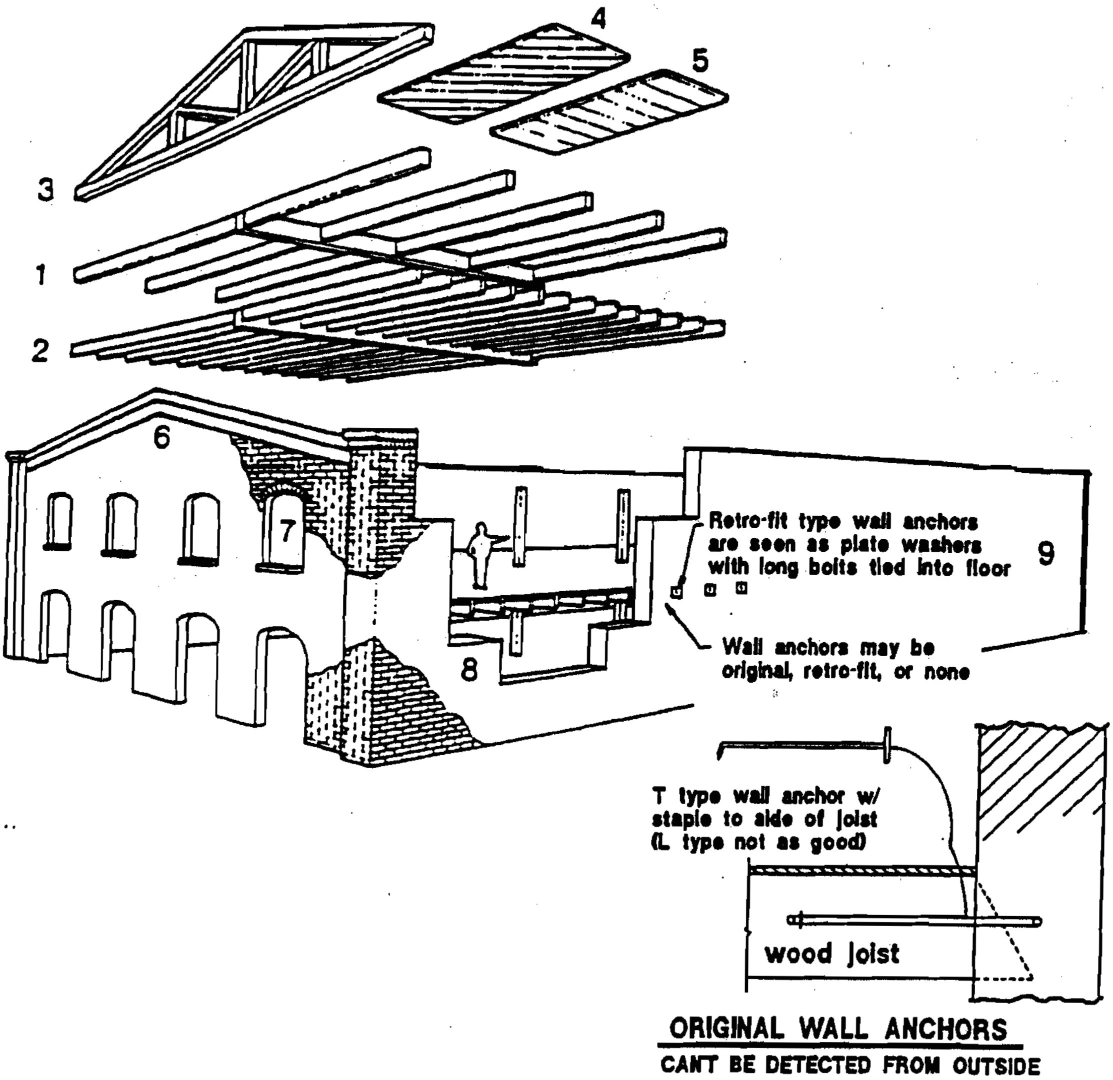
f) Older steel frame buildings with unreinforced or lightly reinforced masonry infill, often shed this weak, brittle covering as they flex to resist the quake (see BF-15).

g) Broken bricks often line the streets where these buildings are located and people can be trapped on the sidewalk, auto, etc.

UNREINFORCED MASONRY URM

Roof/floor span systems:
1. wood post and beam (heavy timber)
2. wood post, beam, and joist (mill construction)
3. wood truss-- pitch and curve

Roof/floor diaphragms:
4. diagonal sheathing
5. straight sheathing



Details:
6. typical unbraced parapet and cornice
7. flat arch window opennings

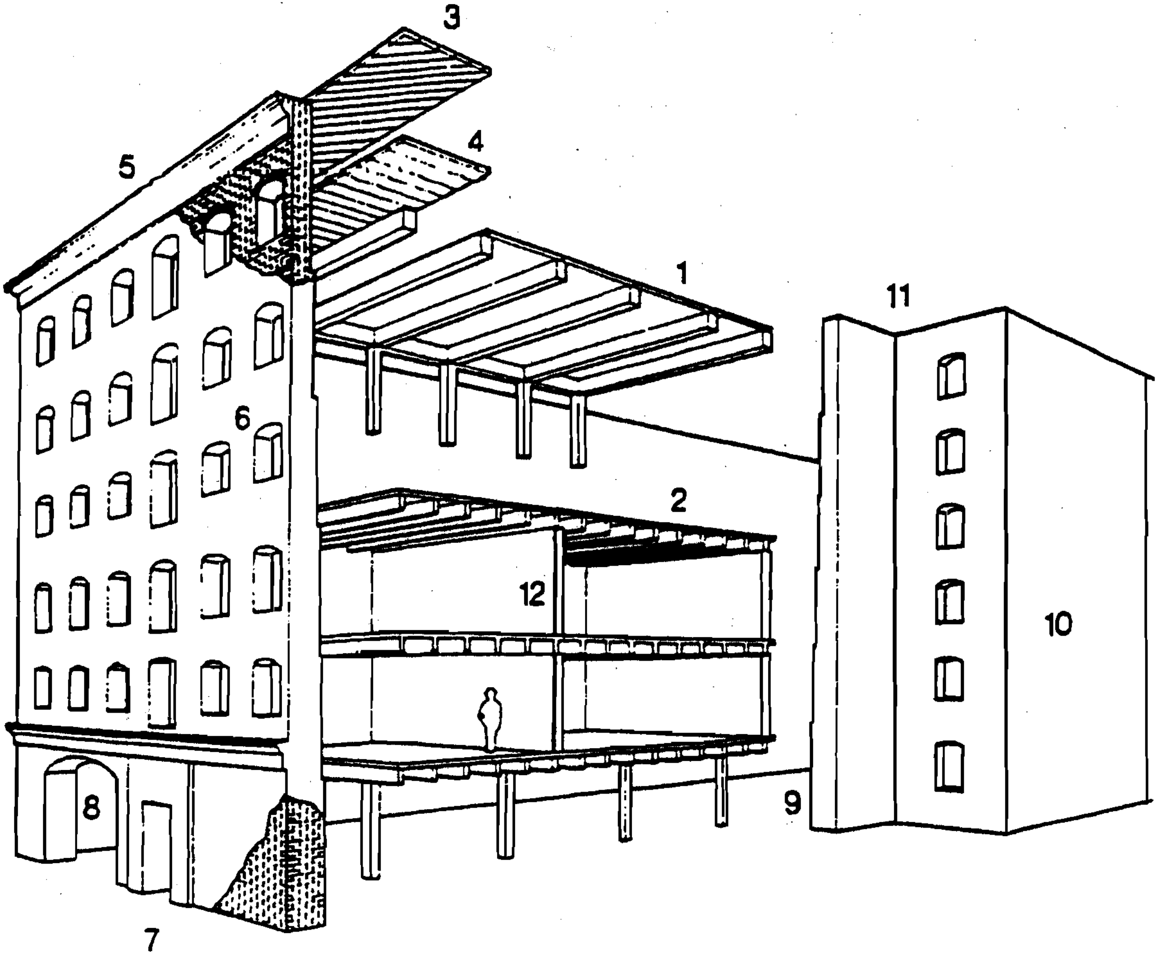
Wall systems:
8. bearing wall-- four or more wythes of brick
9. typical long solid party wall

Figure BF-13

UNREINFORCED MASONRY URM

Roof/floor span systems:
1. wood post and beam (heavy timber)
2. wood post, beam, and joist (mill construction)

Roof/floor diaphragms:
3. diagonal sheathing
4. straight sheathing



Details:
5. typical unbraced parapet and cornice
6. flat arch window opennings
7. typical penetrated facade of residential buildings
8. large opennings of ground floor shops

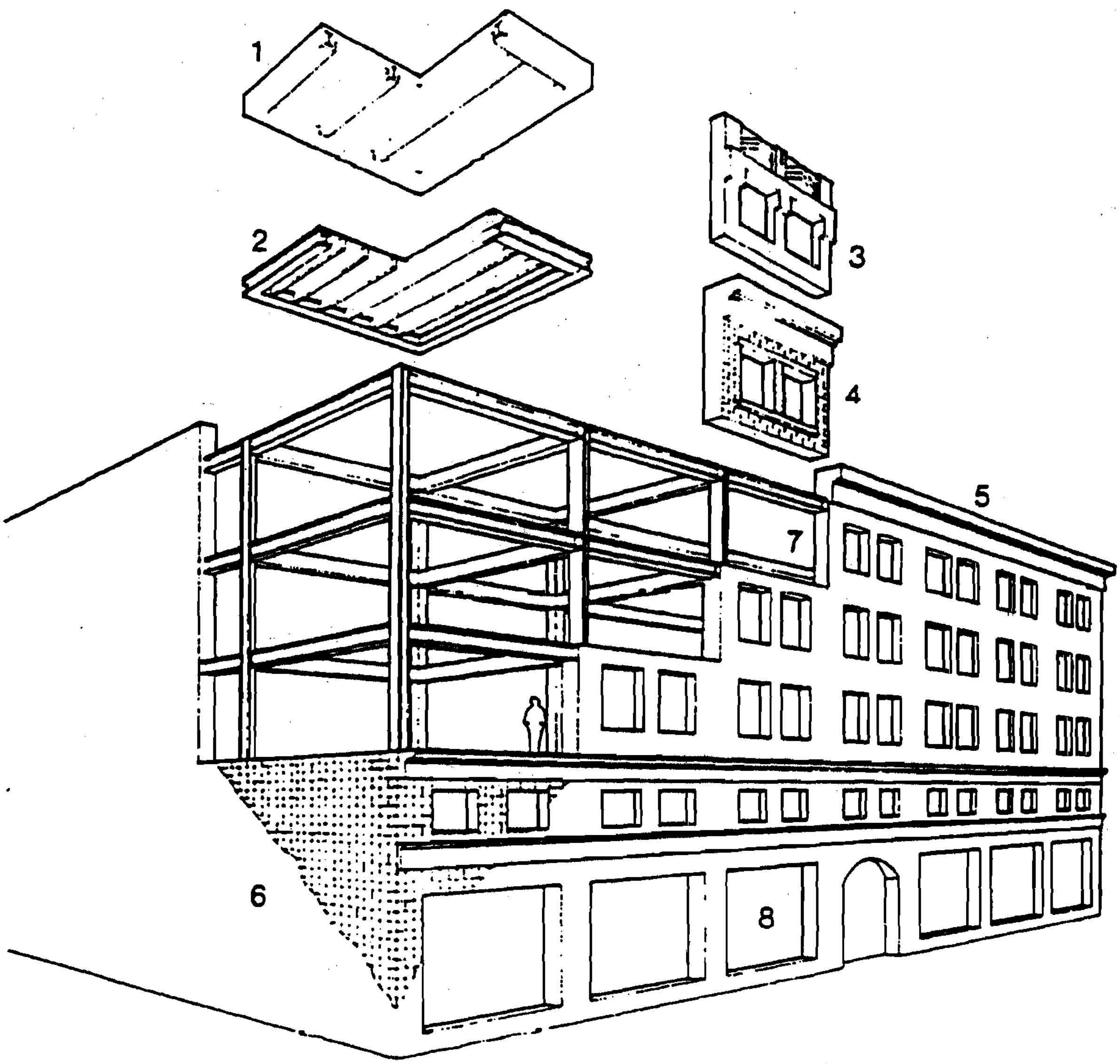
Wall systems:
9. bearing wall–four to eight wythes of brick
10. typical long solid party wall
11. light/ventilation wells in residential bldg
12. non-structural wood stud partition walls

Figure BF-14

STEEL FRAME WITH URM INFILL

Roof/floor span systems:
1. steel framing with concrete cover
2. wood floor joist and diaphragm (diagonal and straight)

Wall systems:
3. non-load-bearing concrete wall
4. non-load-bearing unreinforced masonry cover wall



Details:
5. unreinforced and unbraced parapet and cornice
6. solid party walls

Openings and wall penetrations:
7. window penetrated front facade
8. large openings of street level shops

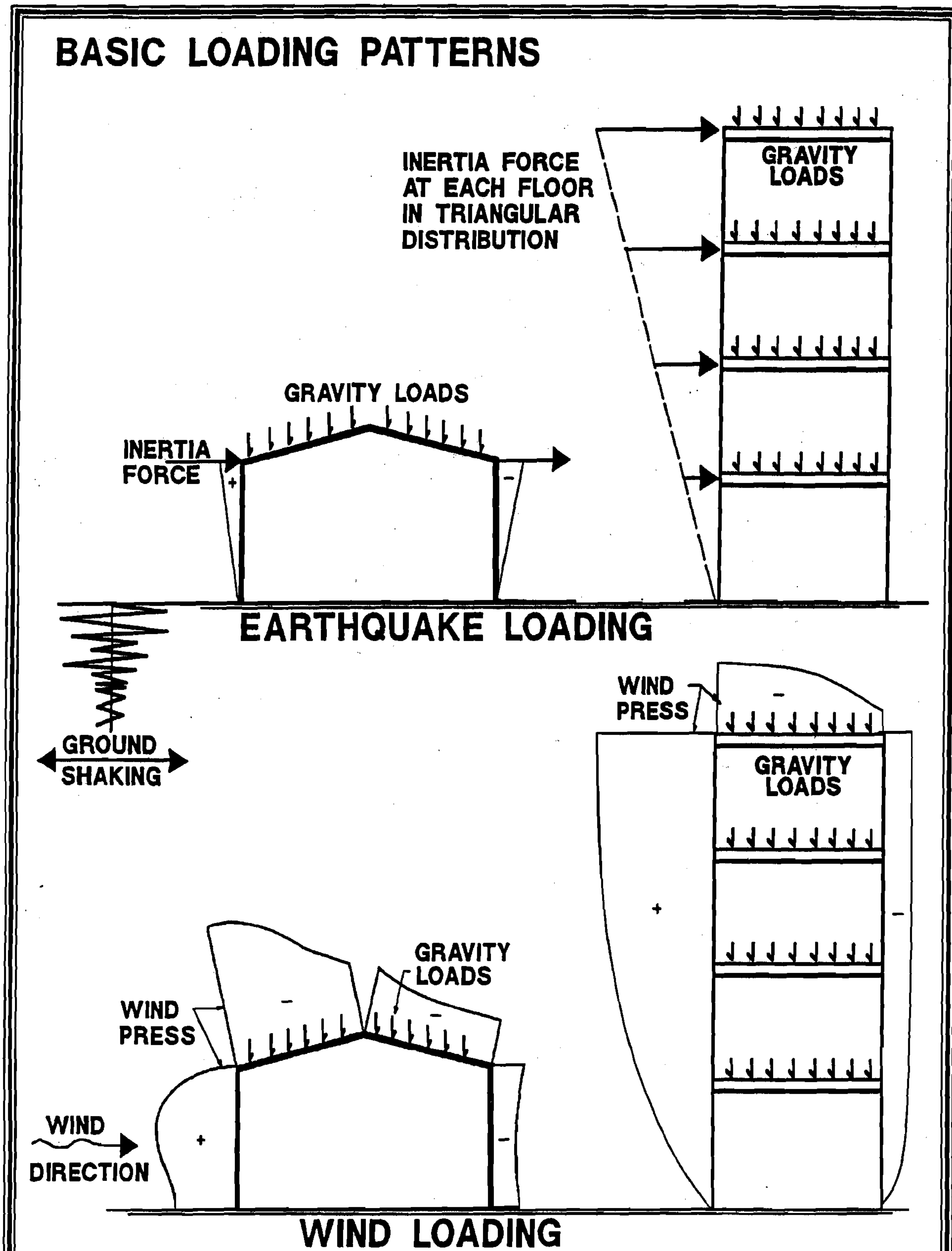
Figure BF-15

BASIC STRUCTURAL LOADING (See BF-16, BF-17)

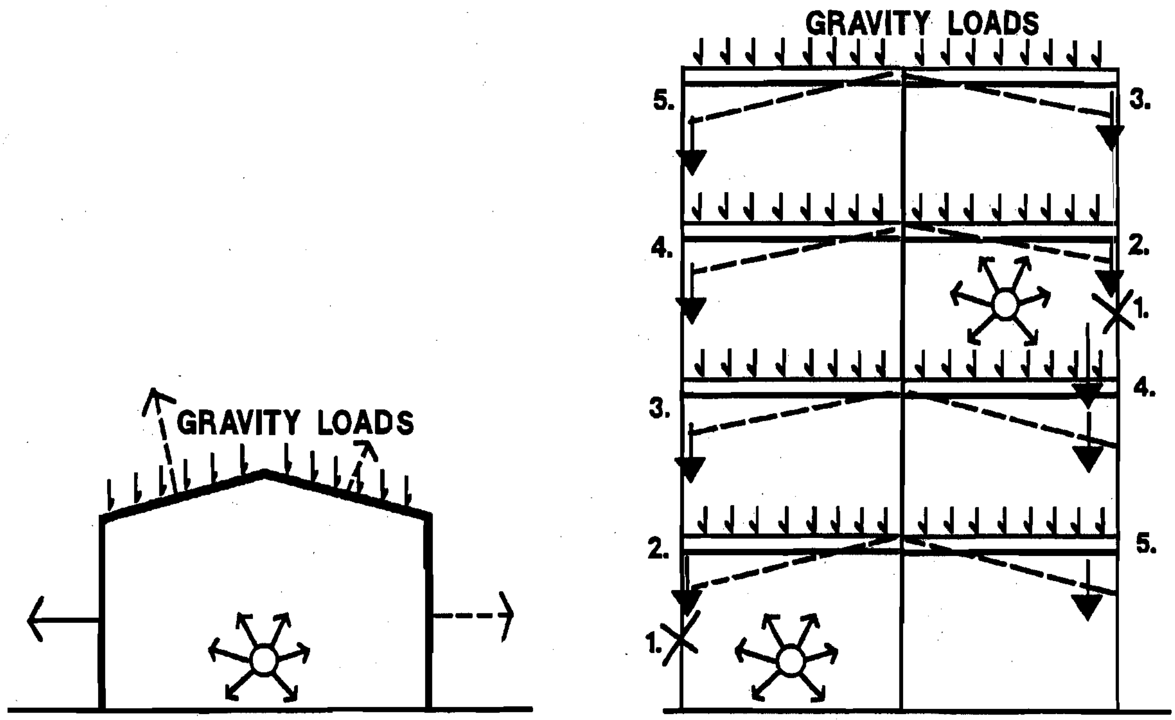
1. **Earthquake-** Some of the most destructive effects caused by earthquake shaking are those that produce lateral loads in a structure. The input shaking causes the foundation of a building to oscillate back and forth in a more or less horizontal plane. The building mass has inertia and wants to remain where it is and, therefore, lateral forces are exerted on the mass in order to bring it along with the foundation. This dynamic action can be simplified (in an upside down way) as a group of horizontal forces that are applied to the structure in proportion to it's mass, and to the height of the mass above the ground, as shown in BF-16. In multi-story buildings with floors of equal weight and relatively light walls, the loading is further simplified as a group of loads, each being applied at a floor line, and each being greater than the one below in a triangular distribution. Seismicly resistant structures are designed to resist these lateral forces through inelastic action and must, therefore, be detailed accordingly. These loads are often expressed in terms of a percent of gravity weight, and can vary from a few percent to near fifty percent of gravity weight. There are also vertical loads generated in a structure by earthquake shaking, but as mentioned previously, these forces rarely overload the vertical load resisting system. Earthquake induced vertical forces have caused damage to heavy concrete structures with high dead load compared to design live load. These vertical forces also increase or decrease compression forces in the columns. (Increased compression that overloads columns or decreased compression that reduces column bending strength).

2. **Wind-** (see BF-16) forces are generated on the exterior of the building based on it's height, local ground surface roughness (hills, trees, other buildings) and the square of the wind velocity. The weight of the building, unlike the earthquake condition, has little effect on wind forces, but is helpful in resisting uplift. Unless the structure is penetrated, all the forces are applied to the exterior surfaces of the building, as contrasted to earthquakes, where as an example both exterior and interior walls are loaded proportionally to their weight.

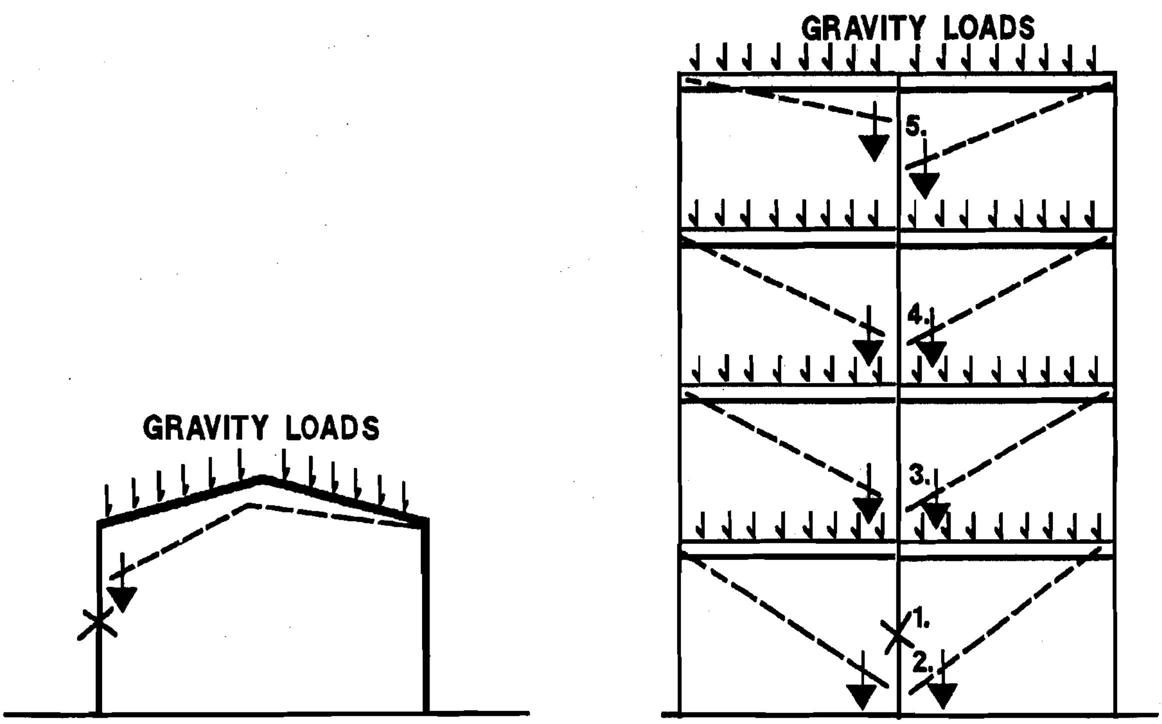
   Wind pressures act inward on the windward side of a building and outward on most other sides and most roof surfaces. Special concentrations of outward force, due to aerodynamic lift, occur at building corners and roof edges, especially overhangs. The overall structure must be designed for the sum of all lateral and uplift pressures and individual parts must be designed to resist the outward and inward pressure concentrations, and must be connected to supporting members (beams, columns, walls, foundation) to form a continuous resistance path. Forces are also generated on structures by airborne missiles that vary in size from roofing gravel to entire sections of roofs.


BASIC LOADING PATTERNS
INERTIA FORCE
AT EACH FLOOR
IN TRIANGULAR
DISTRIBUTION
GRAVITY
LOADS
GRAVITY LOADS
INERTIA
FORCE
+
-
EARTHQUAKE LOADING
GROUND
SHAKING
WIND
PRESS
-
GRAVITY
LOADS
+
-
GRAVITY
LOADS
WIND
PRESS
-
-
WIND
DIRECTION
+
-
WIND LOADING
Figure BF-16

BASIC LOADING PATTERNS



EXPLOSION RAPIDLY EXPANDING GAS MUST ESCAPE



CONSTRUCTION BRACING, URBAN DECAY, OVERLOAD

Figure BF-17

3. **Explosion-** (see BF-17) In industrial accidents and natural gas explosions that occur within a structure, the weakest parts of the enclosures are blown away as the pressure escapes. If the wall and roof coverings in frame buildings are well enough attached to the structure, the frame may be blown away as well. In large explosions, precast concrete walls, slabs, and even columns can be blown out, leading to conditions that will produce a progressive collapse as illustrated in BF-18. Progressive collapse starts with the initial damage due to the outward force of the explosion, but then the gravity load drives the structure to the ground due to the instability caused by the blown out vertical support. It takes a very large explosion to damage a reinforced concrete building as long as there are enough lightly enclosed openings that will allow the pressure to escape. However, lighter wood, steel, and precast concrete buildings can be leveled by large explosions, as horizontal and vertical enclosing planes are blowing out leading to an over all loss of stability.

   When large bombs have been placed immediately adjacent to structures the effects have also been very devastating. The shock waves radiate out in all directions causing lateral and upward pressures in nearby buildings. Missiles of all sorts are created, such as glass, building contents, and small building parts, that can have devastating effects, especially on humans. However, since the pressures dissipate so rapidly and have the greatest effect on objects in their direct path, one can observe many conditions where a strong, resistant structure will provide shading from the effects.

   In the Oklahoma City bombing, according to Dr. Eve Hinman, (Specialist in blast design at Failure Analysis Assoc., Menlo Park, CA) the shock wave radiated from the detonation point in all directions with initial pressures in the range of 5000 p.s.i. Although the pressure dissipates as a function of the cube root, (a location twice the distance from the blast that another will feel only one eight the pressure) structures can be severly shattered and/or shredded by it's effects, especially the upward pressures.

4. **Flood-** (see BF-19) Forces are generated on buildings due to hydrostatic lateral and lifting pressure, hydrodynamic forces, and debris impacts. Hydrostatic pressures can highly load foundation and basement walls and lift structures, when water level is not equalized between exterior and interior spaces. River and ocean currents will load frontal and side walls that are submerged, and ocean waves and step-up flows can produce pressures as high as 1000 psf. Debris, varying in size from floating wood pieces to floating structures, can impact a building causing anything from broken windows to a total collapse.

5. **Construction Bracing, Urban Decay, Overload-** These sudden collapses, usually occur due to gravity loading when a vertical support is either, inadequate, overloaded by snow, overloaded due to plugged roof drain, or reduced in capacity due to age, corrosion, or non-engineered alteration. Failures of this type occur all too frequently, but most often effect only one structure at a time. In some cases very hazardous conditions have been left standing in this type of collapse, i.e., multi-story URM walls left unsupported when wood floors pancaked.

PROGRESSIVE COLLAPSE

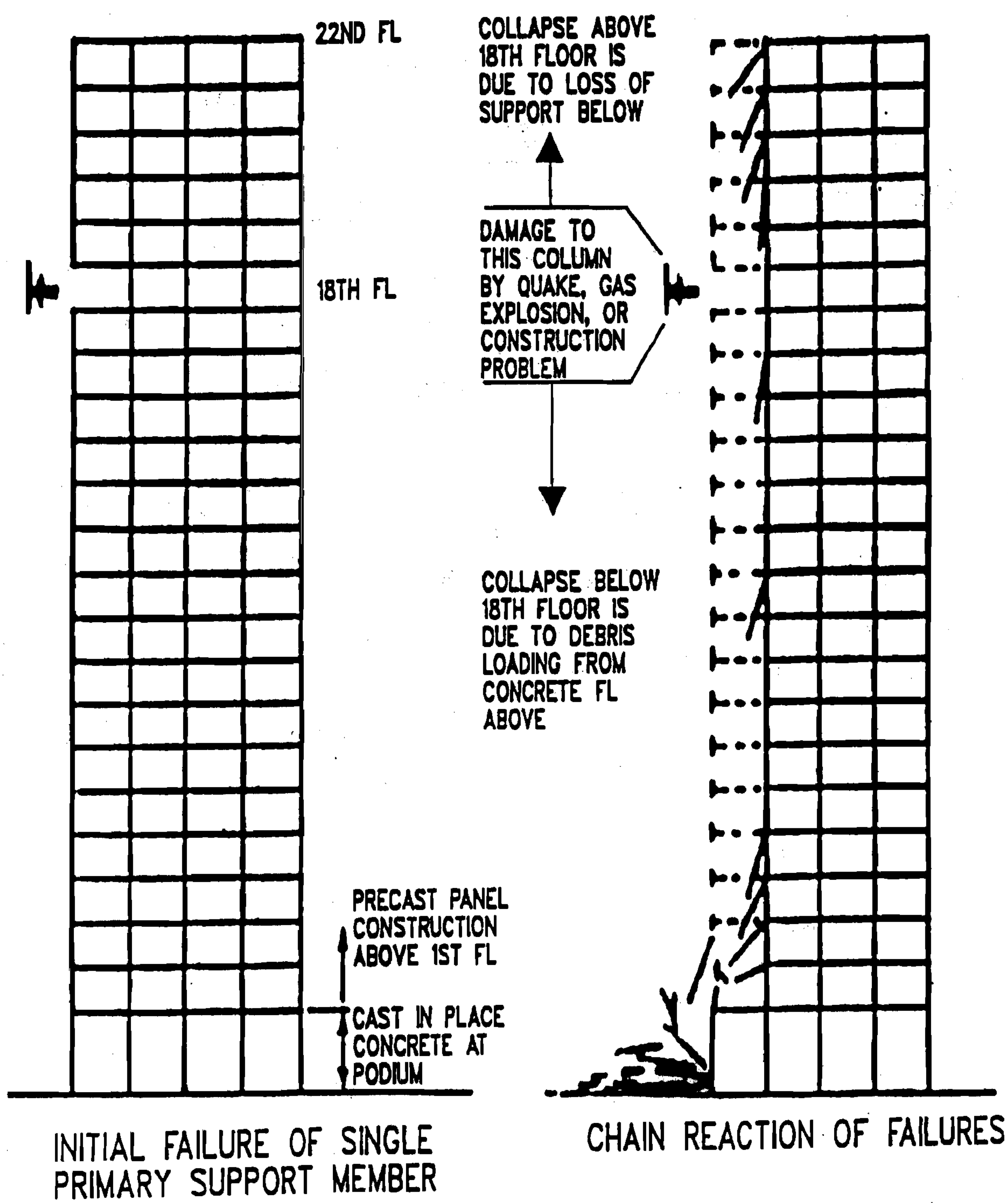
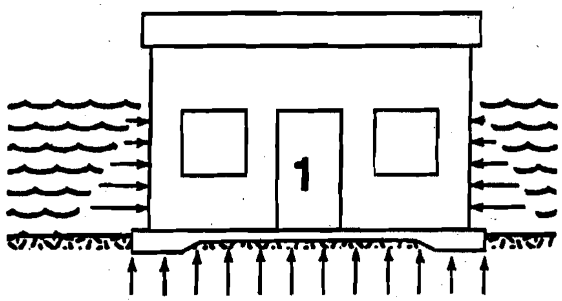
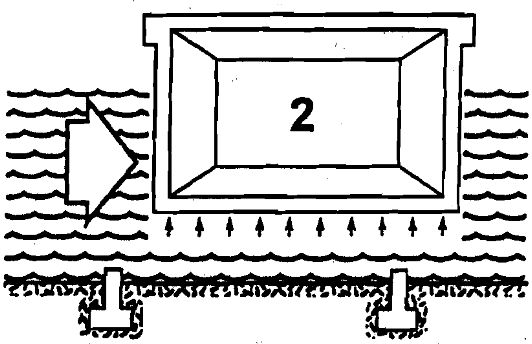


Figure BF-18

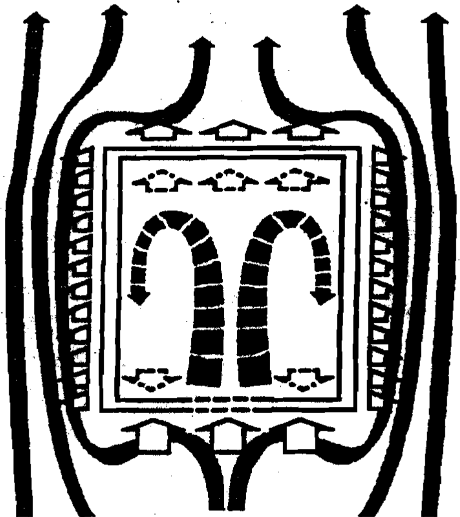
BASIC LOADING PATTERNS • FLOOD



HYDROSTATIC LATERAL AND UPLIFT PRESSURES PERPENDICULAR TO ALL SURFACES OF EMPTY BLDG

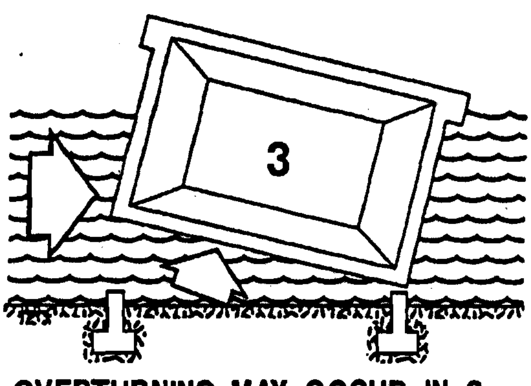


TRANSLATION MAY RESULT FROM COMBINATION OF BUOYANCY AND HYDRODYNAMIC FORCES

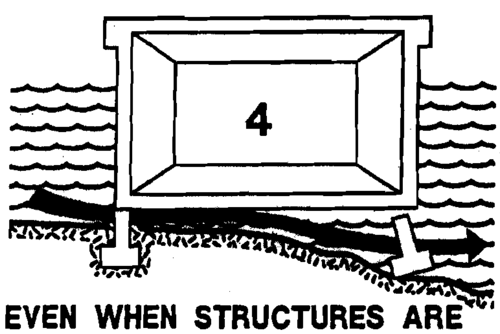


PLAN VIEW

HYDRODYNAMIC FORCES INCLUDE THE IMPACT OF WATER & WAVES ON THE UPSTREAM SIDE, DRAG FORCES ON SIDES, & SUCTION PRESSURE ON TO DOWNSTREAM SIDE. WHEN WATER RUSHES INTO A STRUCTURE (shown dashed) IT IMPACTS THE FACING WALL AND THEN TURNS BACK TOWARDS ITS POINT OF ORIGIN, CAUSING HYDRODYNAMIC FORCES ON INTERIOR ELEMENTS.



OVERTURNING MAY OCCUR IN 2 IF FRICTION, CONNECTIONS, OR UNEVEN WATER INFILTRATION HOLDS ONE EDGE OF BLDG TO FOUNDATION



EVEN WHEN STRUCTURES ARE NOT MOVED, RUSHING WATER CAN CAUSE SCOUR & EROSION AROUND SLABS & FOUNDATIONS

Figure BF-19

BASIC COLLAPSE PATTERNS (See BF-20)

1. Most building collapses occur due to loss of stability; that is, the basic shape is significantly changed when subjected to a combination of forces. The new, changed shape is much less capable of carrying the forces and, therefore, the structure will rapidly continue to change until it finds a new shape that is stable. A typical example of lost stability is that of the slender column, that "gets out of the way of the load by buckling", as the load comes to rest on the ground/foundation. The most common conditions that lead to building collapse are illustrated in BF-20 as:

   a) **Inadequate Shear Strength-** Failure is normally caused by earthquake shaking, but high velocity winds could produce the same effect. It is most commonly seen in wood structures that have weak wall sheathing or walls of insufficient length, but may also be seen in buildings with unreinforced masonry and/or unreinforced concrete wall, and in diagonally braced steel frames. In rare instances it could also occur when reinforced concrete walls are present.

      The basic instability occurs when the gravity load is offset a distance, delta, that is large enough to overcome the shear capacity of walls at a particular level, usually the first story. The horizontal resistance required to maintain stability in the racked condition (parallelogram) illustrated, is proportional to the percent of offset (i.e., when a ten foot high story is offset one foot, then ten percent of the total gravity load above that level is required to keep the parallelogram from becoming flatter).

   b) **Inadequate Beam/Column Joint Strength-** is caused mostly by earthquake shaking of poorly confined concrete. The cycling of the structure when excited by the earthquake causes moment resistant joints to unravel as concrete chunks are stripped away from the reinforcing steel cage. The gravity load can no longer be supported by these columns, and it drives the structure earthward until it stops on the ground or lower floors that have sufficient strength to stop the falling mass. The result of a concrete collapse of this type may be a pancaked group of slabs, a condition where columns are left standing, punched through the slabs, or a group of slabs that are horizontally offset from each other, held apart by broken columns and building contents.

COMMON COLLAPSE PATTERNS

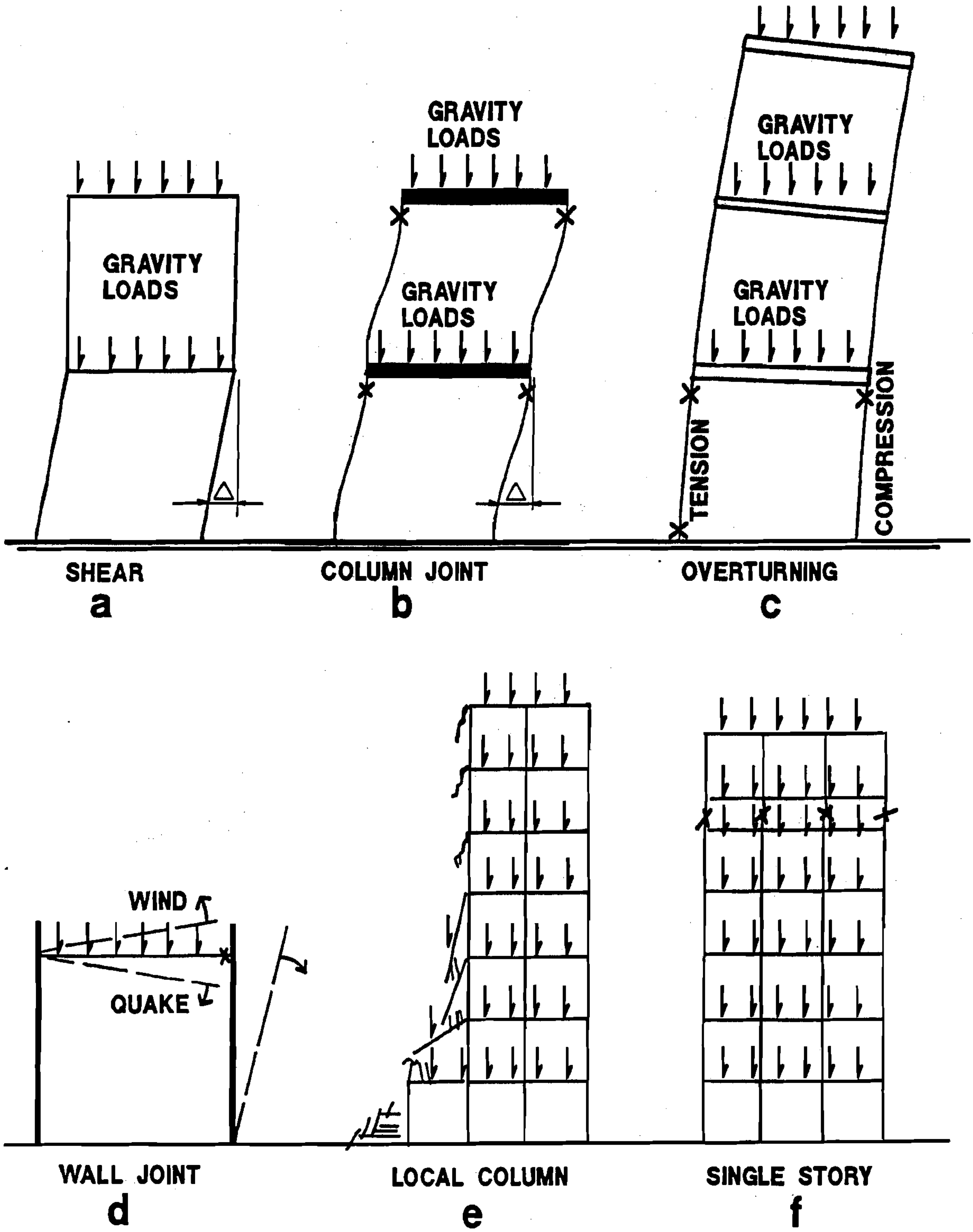


Figure BF-20

c) **Tension/Compression Failure-** caused mostly by earthquakes and may occur in taller structures with concrete shear walls and/or concrete or structural steel frames. The tension that is concentrated at the edges of a concrete frame or shear wall can produce very rapid loss of stability. In walls, if the reinforcing steel is inadequately proportioned or poorly embedded, it can fail in tension and result in rapid collapse of the wall by overturning. A more common condition occurs, when tension causes the joints in a concrete frame to lose bending/shear strength, as previously discussed, a rapid degradation of the structure can result in partial or complete pancaking as in beam/column failure.

The previously discussed failure of Pino Suarez Tower is an example of how poorly proportioned, steel structures can catastrophically overturn, due to a compression failure of the columns.

d) **Wall To Roof Interconnection Failure-** Stability is lost in this case since the vertical support of the roof/floor is lost, as well as the horizontal out of plane support of the wall. This condition could be triggered by any of the destructive forces previously mentioned.

e) **Local Column Failure-** can lead to loss of stability and/or progressive collapse in a part of a structure, and may, again, be caused by any of the previously mentioned forces. Precast concrete and structures that have wood floors tend to be more susceptible to a progressive type failure (see BF-18), due to the lack of continuity of these construction configurations.

f) **Single Floor Collapse-** has occurred in earthquakes due to pounding or vertical irregularities that focus the damaging effects to a single story.

In summary, in most all collapses (except cases when wind causes lifting), the driving force is the gravity load acting on a structure that has become unstable due to horizontal offset or insufficient vertical capacity. In addition, subsequent lateral loads from wind or aftershocks can increase the offset, exaggerating the instability. The structure is often disorderly as it collapses. Some parts may remain supported by un-collapsed adjacent bays as tension structures.

The issue in US&R is not the academic one of how the structure collapsed in order to improve future construction, but what additional collapse is possible and how stable is the existing configuration. This will be discussed further in the Hazard Identification Section.

EARTHQUAKE COLLAPSE PATTERNS

1. **The basic principles are:**

   a) **Earthquake shaking caused damage to structural loading system.**

   b) **Gravity caused collapse.**

   c) **Redundancy and ductile behavior can prevent or reduce extent of collapse.**

   d) **Brittle behavior enhances possibility and increases extent of structural collapse.**

2. Based on previous earthquakes, the ATC-21 building types can be further divided into four separate groups, with each exhibiting a distinctive collapse pattern. These groups are:

   a) **LIGHT FRAME-** Mostly wood frame

   b) **HEAVY WALL-** URM, Tilt-up, and other low raise buildings with concrete and masonry walls

   c) **HEAVY FLOOR-** Concrete frame buildings and Highway bridges

   d) **PRECAST CONCRETE BUILDINGS-** with fairly heavy floors and some heavy walls

3. **Light Frame Collapse Patterns** (see BF-21, BF-22)

   a) Collapse usually occurs when lower walls have insufficient strength to resist the lateral forces and rack (become parallelograms).

   b) If there is a sufficiently heavy load on these walls they can completely collapse as the wall top moves sideways a distance equal to the height as shown in BF-21.

   c) This causes the structural collapse to be in the form of part or all of the building being projected away from it's original foundation by the height of the story walls that fail.

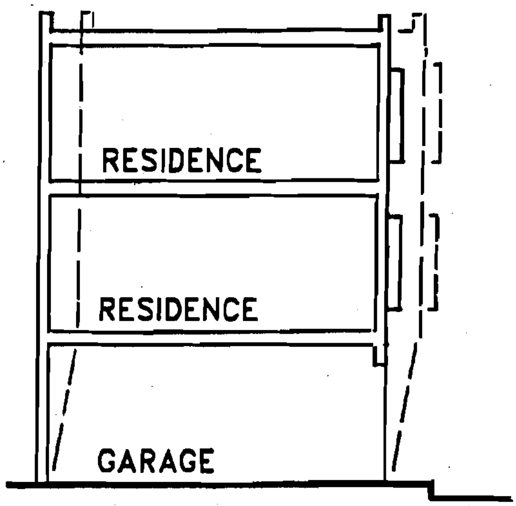
   d) When the bottom story of a multi-story light frame structure fails in this way, additional stories can also collapse due to the impact of the first story hitting the ground.

   e) This type of collapse usually leaves many voids that are fairly easily accessible.

   f) There is great danger of fire due to the combination of broken gas (or other fuel) lines and the combustible debris.

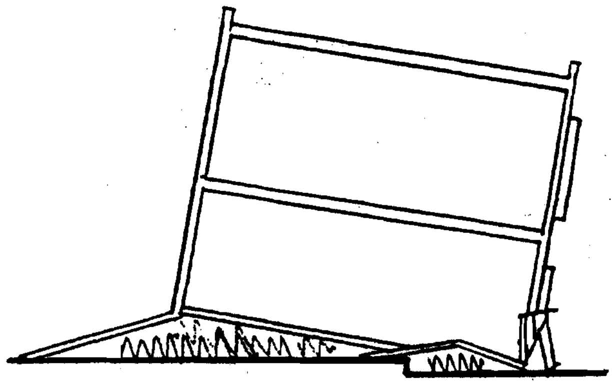
LIGHT FRAME COLLAPSE PATTERNS

BUILDING IS INITIALLY OFFSET BY EARTHQUAKE FORCES ACTING ON 1ST STORY WALLS THAT HAVE LOW SHEAR STRENGTH, DUE TO LARGE DOOR OPENINGS



INITIAL CONDITION

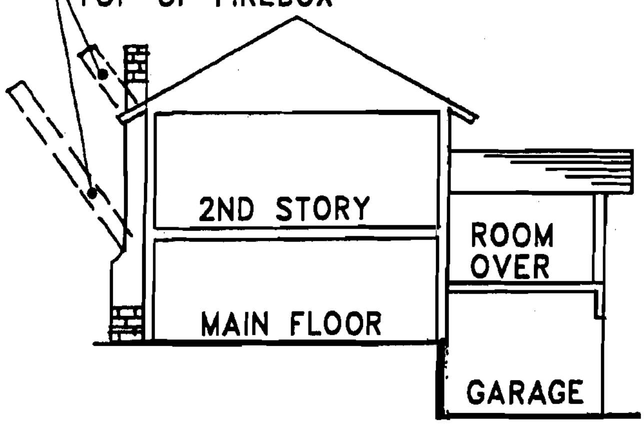
SINCE 1ST STORY WALLS ARE MORE THAN ADEQUATE TO SUPPORT RELATIVELY LT. WT. STORIES ABOVE, THEY KEEP THEIR ORIGINAL LENGTH & PROJECT THE UPPER STORIES AWAY FROM THE BLDG EDGE BY THE LENGTH OF THE IST STORY WALLS.



COLLAPSE PROJECTS STRUCTURE BEYOND IT'S BOUNDARY

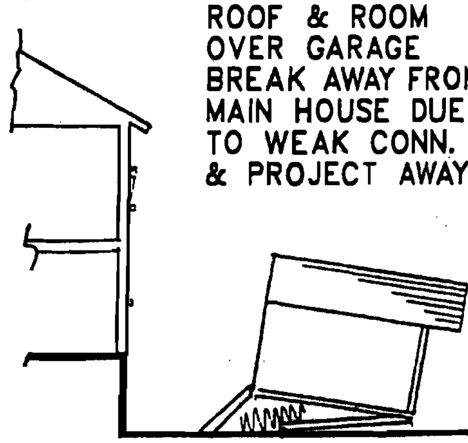
TWO TO FOUR STORY RESIDENTIAL STRUCTURES

CHIMNEYS BREAK OFF AT ROOF LINE OR AT TOP OF FIREBOX



INITIAL CONDITION

ROOF & ROOM OVER GARAGE BREAK AWAY FROM MAIN HOUSE DUE TO WEAK CONN. & PROJECT AWAY

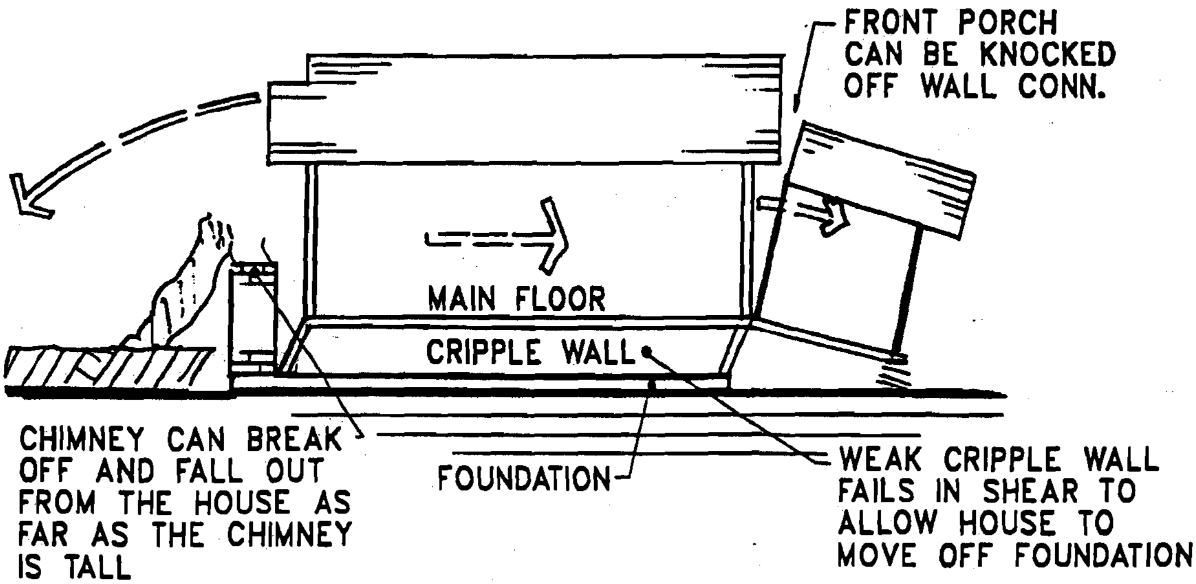


COLLAPSE PROJECTS OFFSET PART OF HOUSE AWAY

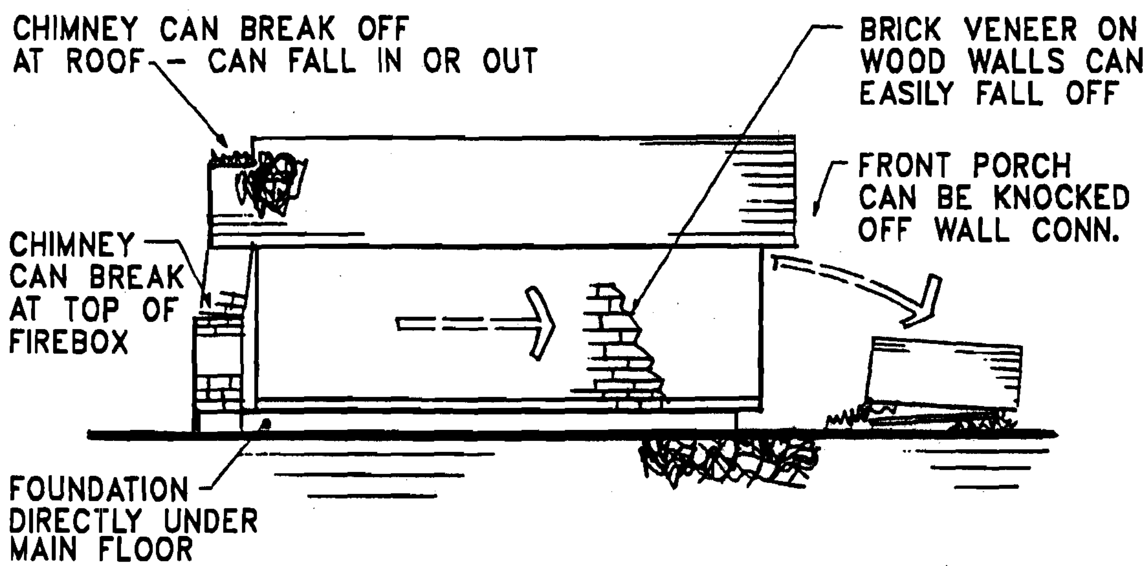
SPLIT LEVEL RESIDENCE STRUCTURE

Figure BF-21

LIGHT FRAME COLLAPSE PATTERNS



HOUSE WITH CRIPPLE WALL UNDER FLOOR



HOUSE WITH FOUNDATION CONNECTING TO FLOOR

Figure BF-22

4. **Heavy Wall Collapse Patterns** (see BF-23, BF-24)

a) Collapse is usually partial and is strongly related to the heavy, weak bearing walls falling away from the floors.

b) In URM buildings the walls normally fall away from their original position, but, most often, don't project out as far as their height. The combination of the weak interconnection of the masonry pieces and gravity tend to cause the debris to stay within ten to fifteen feet of the building face.

Note, in collapse due to failure of interior columns or due to fire, it is possible to have the very precarious situation of multi-story heavy walls that are left standing without any laterally supporting floors/roof. For this case it is probable that the wall could fall such that they extend their full height along the ground.

c) Walls in Tilt-up buildings also, normally fall away from the roof or floor edge, but since they are very strong panels, the top of the wall will fall as far away from the building as it's height.

d) The falling walls can cause the roof and floors that they support to collapse in patterns of Lean-to, Vee, Pancake, and Cantilever (see URM-4PAT).

LEAN-TO can be formed when one exterior wall collapses, leaving the floor supported at one end only.

V-SHAPE would occur when an interior supporting wall or column fails.

PANCAKE can occur when all vertical supporting members fail and most of the floors collapse on top of one another. This is more common in Heavy Floor buildings.

CANTILEVER is a pancake collapse where some of the floor planes extend out as unsupported members.

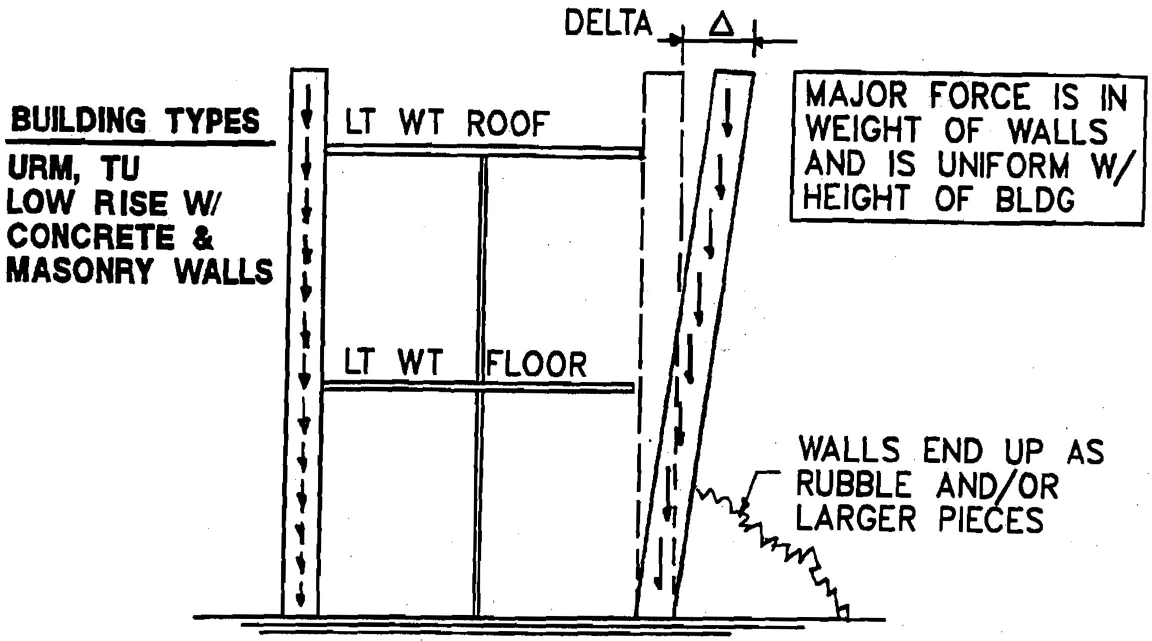
e) When property line walls fall on an adjacent, lower buildings, these structures will usually have some sort of roof/floor collapse.

f) When the wood roof and/or floors collapse, many easily accessible voids can be created.

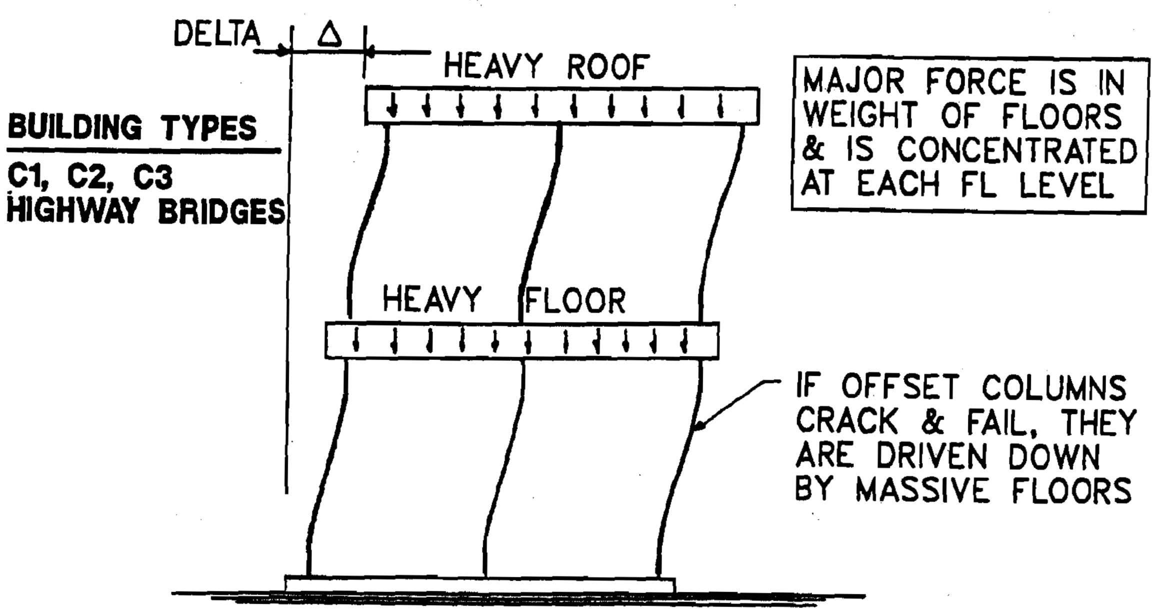
g) Areas adjacent to the walls where the heavy debris fall often contain very badly injured or dead victims.

h) The combination of broken gas lines and debris can lead to fire.

STRUCTURAL COLLAPSE PATTERNS



HEAVY WALL STRUCTURES



HEAVY FLOOR STRUCTURES

Figure BF-23

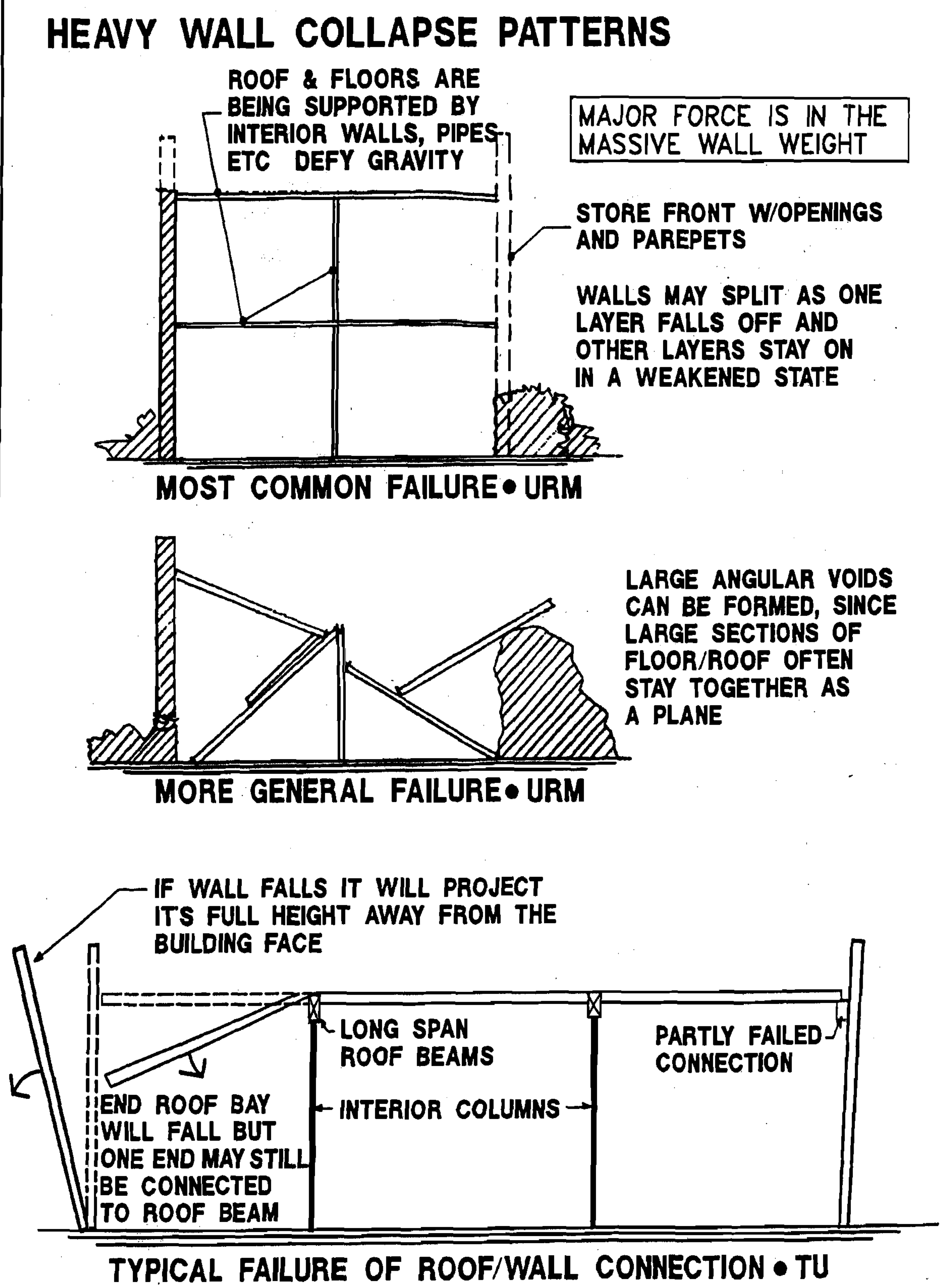
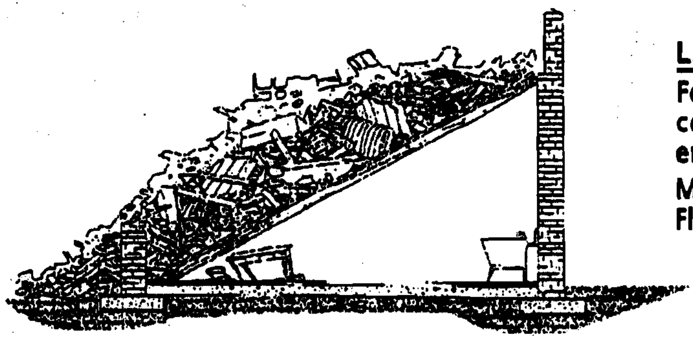

HEAVY WALL COLLAPSE PATTERNS
ROOF & FLOORS ARE BEING SUPPORTED BY INTERIOR WALLS, PIPES ETC DEFY GRAVITY
MAJOR FORCE IS IN THE MASSIVE WALL WEIGHT
STORE FRONT W/OPENINGS AND PAREPETS
WALLS MAY SPLIT AS ONE LAYER FALLS OFF AND OTHER LAYERS STAY ON IN A WEAKENED STATE
MOST COMMON FAILURE • URM
LARGE ANGULAR VOIDS CAN BE FORMED, SINCE LARGE SECTIONS OF FLOOR/ROOF OFTEN STAY TOGETHER AS A PLANE
MORE GENERAL FAILURE • URM
IF WALL FALLS IT WILL PROJECT IT'S FULL HEIGHT AWAY FROM THE BUILDING FACE
LONG SPAN ROOF BEAMS
PARTLY FAILED CONNECTION
END ROOF BAY WILL FALL BUT ONE END MAY STILL BE CONNECTED TO ROOF BEAM
INTERIOR COLUMNS
TYPICAL FAILURE OF ROOF/WALL CONNECTION • TU

Figure BF-24

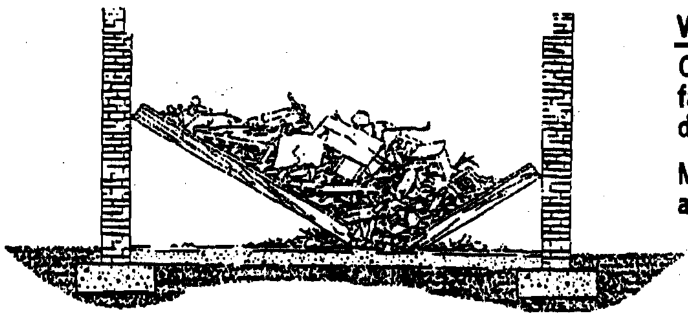
URM WALL / WOOD FLOOR COLLAPSE PATTERNS



LEAN-TO FLOOR COLLAPSE

Formed when one wall collapses, leaving other end in hazardous condition

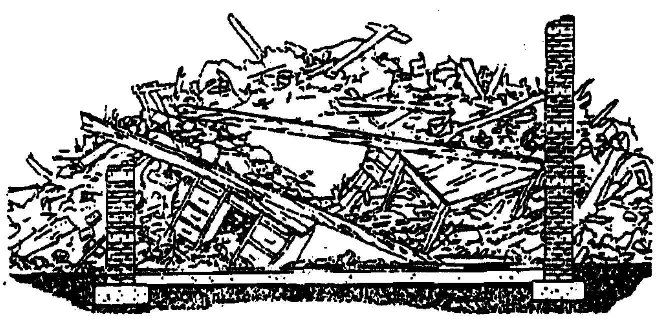
May also occur in TU, Heavy Floor and Precast Conc.



V-SHAPE FLOOR COLLAPSE

Occurs when interior support fails. More common in urban decay/overloaded column failure

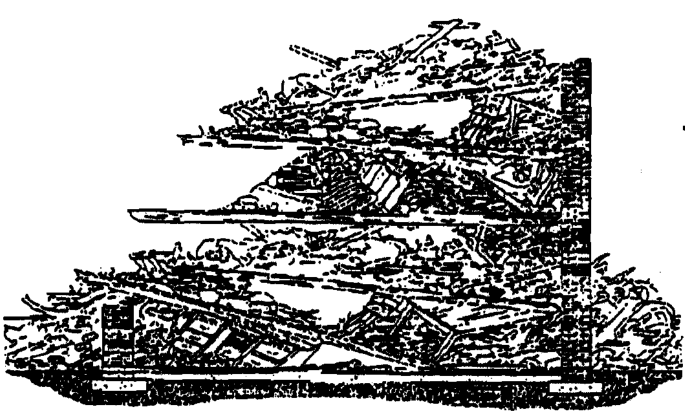
May also occur in Heavy Floor and Precast Conc. bldgs



PANCAKE FLOOR COLLAPSE

Occurs when most all vertical supporting members fail and allow floors to collapse on top of each other.

More common for Heavy Floor and Precast Conc. bldg.



CANTILEVER FLOOR COLLAPSE

(pancake with extended floors)

May also occur in Heavy Floor and Precast Concrete buildings.

Figure URM-4PAT

5. **Heavy Floor Collapse Patterns** (see BF-23, BF-25, BF-26)

a) Collapse can be partial to complete. It is usually caused when columns or walls, weakened by earthquake motion, are unable to support the heavy floors.

b) The collapse patterns can be the several shown on BF-25 and BF-26, but most all share the pattern of thin void spaces forming within the original plan area of the building.

c) These heavy floor structures usually fall on themselves, but they can project laterally as they fall, if the columns and/or walls are strong enough to not fracture. That is, the columns can fail due to hinging at the top and bottom, and then the collapse looks more like the light frame type.

d) The voids can be very difficult to access, since even though the heavy floors may have dropped tens of feet they are still usually well interconnected with reinforcing steel.

e) The height of remaining voids between floors in pancaked buildings will depend on what projections the slabs originally had (beam stems, flat slab drops) and partly crushed contents.

f) Overturned, normally taller structures with shear walls, will often fail due to tension/ shear failure at the base. In this case the structure can project sideways by it's full height.

g) Tall, moment frame structures, where tension to compression reversal causes an almost explosive failure of exterior columns, may overturn, but more often they will collapse within their plan boundaries due to high gravity forces.

h) Many partially collapsed concrete frame structures will contain parts of slabs and/or walls that are hanging off an un-collapsed area. This has been observed in corner buildings when only the street-front bays collapse due to torsion effects, and in long buildings or those with several wings, where some bays do not collapse.

i) Pounding can cause one floor to collapse, leaving a difficult problem to assess, due to remaining floors being overloaded etc.

j) Fire is usually not a problem in this type of collapse.

HEAVY FLOOR COLLAPSE PATTERNS

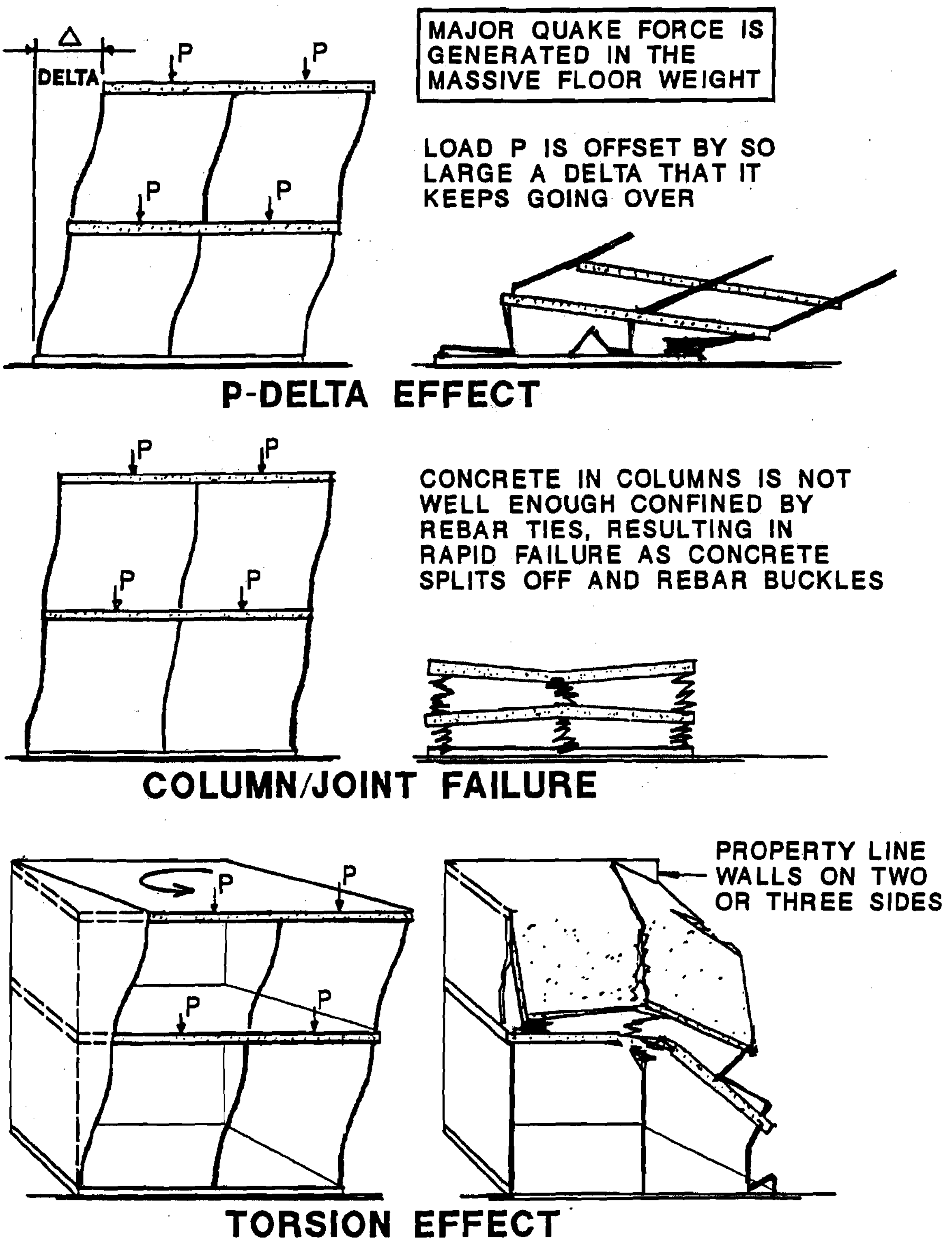


Figure BF-25

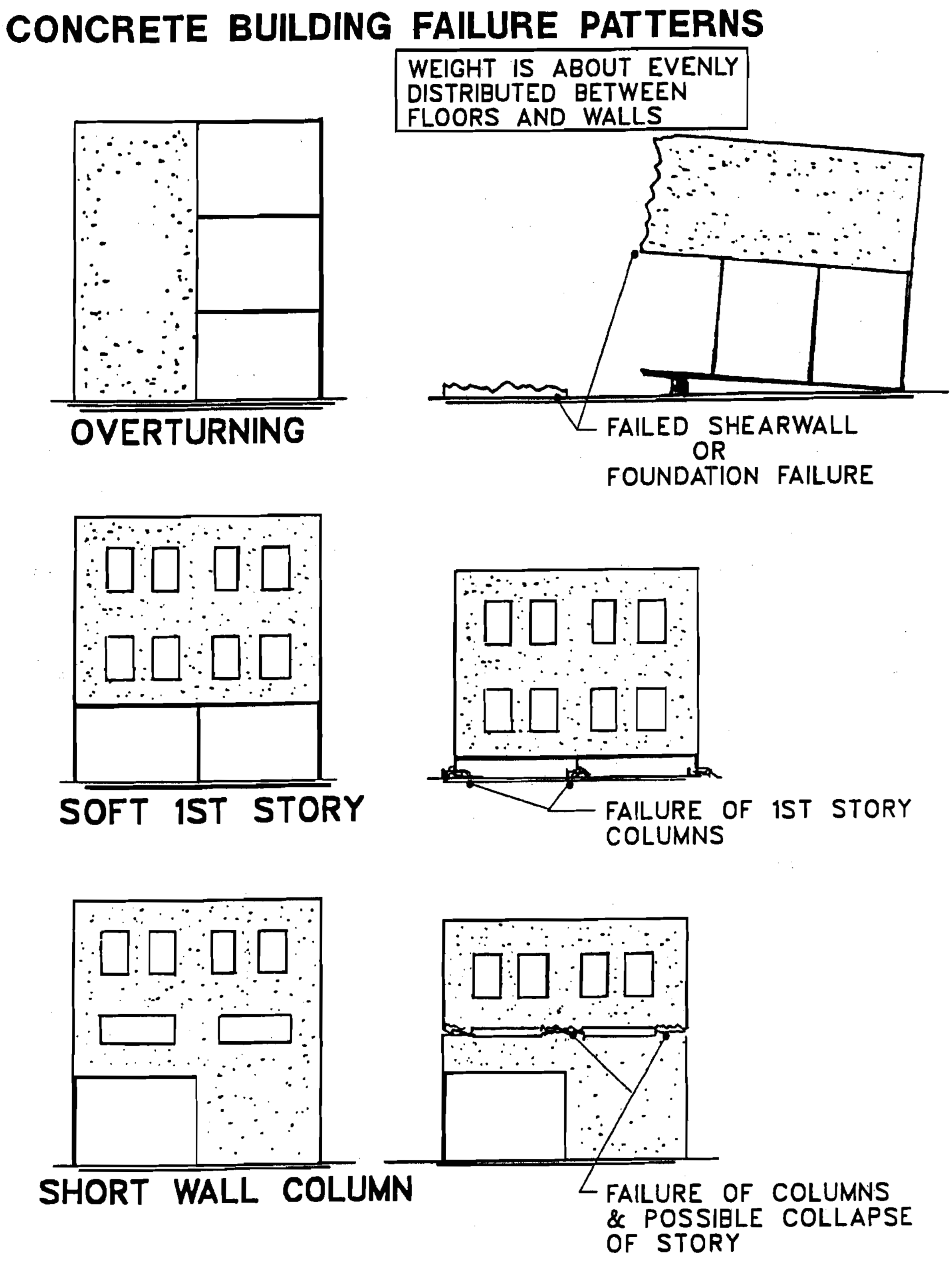

CONCRETE BUILDING FAILURE PATTERNS
WEIGHT IS ABOUT EVENLY DISTRIBUTED BETWEEN FLOORS AND WALLS
OVERTURNING
FAILED SHEARWALL OR FOUNDATION FAILURE
SOFT 1ST STORY
FAILURE OF 1ST STORY COLUMNS
SHORT WALL COLUMN
FAILURE OF COLUMNS & POSSIBLE COLLAPSE OF STORY

Figure BF-26

5. **Precast Collapse Patterns** (see BF-27)

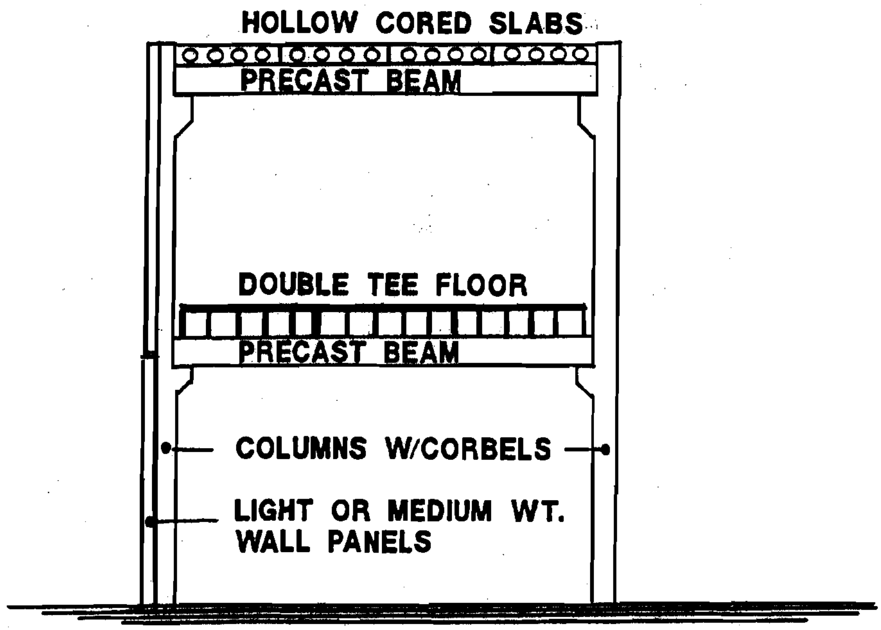
a) Collapse is usually caused when the precast parts become disconnected from each other, and the structure very rapidly looses stability.

b) The collapse normally contains numerous layers of broken and unbroken pieces of slabs, walls, beams, and columns.

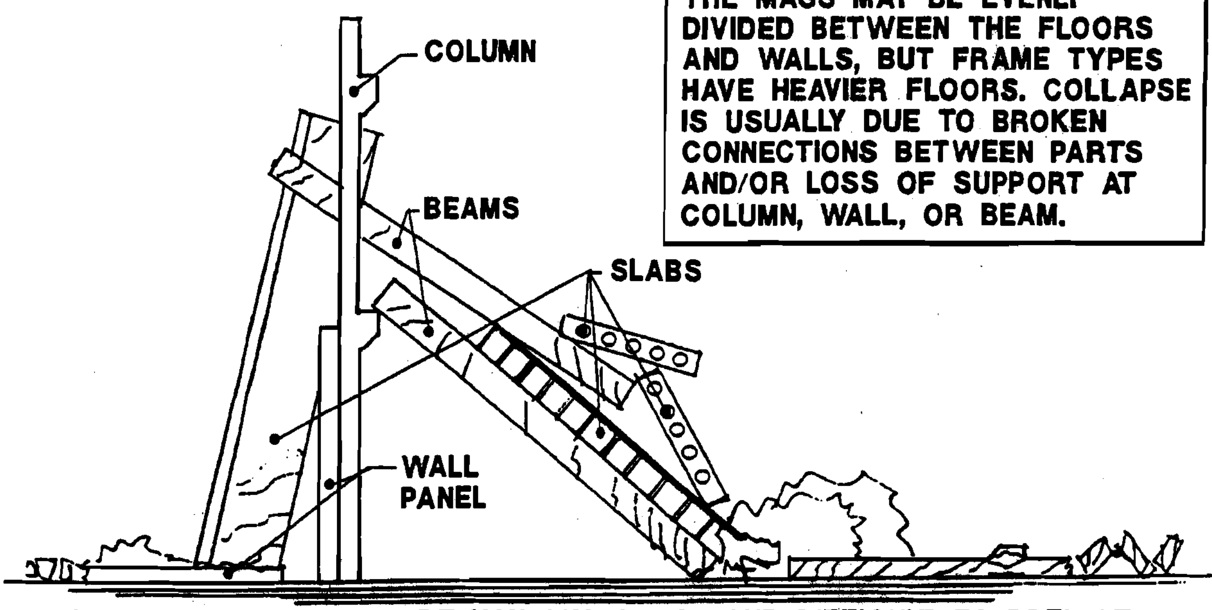
c) It is difficult to predict how far the parts can be projected away from the original structure's position, but gravity normally will drive them downward without projecting them, laterally, away from the building.

d) The voids can be difficult to access, but the slab, etc. can be removed, layer by layer, since interconnections is normally poor to non-existent.

PRECAST CONCRETE COLLAPSE PATTERN



TYPICAL CROSS-SECTION OF FRAME TYPE



THE MASS MAY BE EVENLY DIVIDED BETWEEN THE FLOORS AND WALLS, BUT FRAME TYPES HAVE HEAVIER FLOORS. COLLAPSE IS USUALLY DUE TO BROKEN CONNECTIONS BETWEEN PARTS AND/OR LOSS OF SUPPORT AT COLUMN, WALL, OR BEAM.

COLLAPSE PATTERNS ARE USUALLY VARIED AND DIFFICULT TO PREDICT SINCE THE POORLY CONNECTED PARTS SEPARATE AND FALL DUE TO GRAVITY FORCES AND COLLISIONS WITH OTHER PARTS. IN A TOTAL COLLAPSE, A JUMBLE OF HEAVY, UNCONNECTED PARTS IS FORMED. IN A PARTIAL COLLAPSE, MANY HEAVY PARTS MAY BE LEFT IN A CONFIGURATION WHERE THEY ARE LIKELY TO FALL IN AN AFTERSHOCK

Figure BF-27

WINDSTORM / FLOOD COLLAPSE DAMAGE PATTERNS

1. **Windstorms**- often produce flooding and the damage to structures by both are similar. They normally effect light, poorly, or non-engineered structures, and generate static and dynamic pressures on the exterior surfaces as well as impact forces from missiles/debris. Well engineered structures are designed to resist wind forces by elastic action (as contrasted to the inelastic response that is assumed in earthquake design) and, therefore, it is unusual to have this class of buildings sustain significant wind damage. Water surge, especially that associated with coastal wind storms, can produce damage and even the collapse of the heaviest of engineered structures, but those that are usually affected are lighter structures.

2. **Building Types Damaged by Wind:**

   a) Wood houses

   b) Mobile homes

   c) Wood frame - multi-residential & commercial

   d) Pre-engineered metal buildings

   e) Commercial/industrial buildings with masonry or tilt up walls - especially when wind penetrates openings

   f) Large aircraft hangers - doors get opened by wind, lift on roof - "open structure" damage follows

   g) Buildings with high walls and/or long span roof.

3. **Most Common Wind Collapse**

   a) Part or all of light roof is blown off and walls collapse due to lack of lateral support.

   b) Very tall walls are blown in or out causing the roof to collapse.

   c) Light metal buildings collapse after loss of cladding due to buckling or bending failure of long span roof beam/frame or pull out of base connection.

   d) Missile penetrates glass opening or doors blow in, structure changes from "closed" to "open type", roof and/or leeward wall are blown out. Exterior walls may even be masonry or concrete tilts-up in this scenario, and light interior walls can also be badly damaged.

4. **Common Wind Damage-** that could create structural hazards:

   a) Partial removal of roof and/or wall skin in light frame building. Partial loss of lateral load resisting system.

   b) Peeling of outer layer of multi-layer, cavity type, masonry bearing wall (lightly reinforced eastern type construction).

   c) Removal of masonry veneers on wood and metal frame walls, low or high rise buildings.

   d) Removal of roofing materials; clay/concrete tile, shingles, gravel, etc.

   e) All items, a) thru d) can be destructive missiles.

5. **Common Flood Damage**

   a) Structures moved partly or completely off foundations. They can slide if moved completely off - or tumble if one side stays attached.

   b) Broken or tilted foundation walls.

   c) Undermined foundations and slabs on grade.

   d) Buildings impacted by objects as large as residential structures, causing part wall and/ or roof collapse.

STRUCTURAL COLLAPSE ENGINEERING **DAVID J HAMMOND OCT91**

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(Sponsored by U.S. Postal Service) Appendix F - Wind Damage;
Appendix G - Flood Damage.

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